IMPROVING RAINFED CEREAL PRODUCTION AND WATER PRODUCTIVITY IN MALAWI

Modelling field management options in response to current and future climatic conditions

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Abstract

Food insecurity continues to be a chronic problem in Southern Africa and particularly in the Southern African Development Community (SADC) region. Across the region, food shortages are reported every year, especially in countries including Malawi, Swaziland and Zimbabwe. In this research, Malawi was selected as a case study to understand how a sustainable and improved cereal production under rainfed conditions can be achieved by means of water productivity enhancement. The research focused on two of the major cereals grown in the country: maize, which is the staple food for the country, and sorghum, which is regarded as a drought-tolerant crop that survives under adverse climatic conditions.

Poor weather conditions coupled with high population growth and low soil fertility are the major contributory factors to deteriorating food security in Malawi. Although irrigation has the potential to increase agricultural productivity, the technique is underutilised. Rainfed agriculture still dominates in Malawi making food production only possible in the rainy season from November to April. In addition to that, most of the soils are highly weathered and require regularly enhancement of their fertility. Although potential crop yields are high, the average yield in smallholder farming of the last 10 seasons is only 1.6 ton ha^{-1} for maize and 0.7 ton ha^{-1} for sorghum. To make rainfed agriculture the main source of food and livelihood security for rural communities, the yield gap must be reduced.

The research started with an analysis of the socio-economic characteristics of the smallholder farmers in the region. A field survey of 60 farmer households in the Lilongwe and Shire Valley Agricultural Development Divisions (ADD), whose main crops are maize and sorghum, was conducted. These ADDs with different climates and agronomical management practices were selected as pilot areas. Results indicate that the smallholder farmers are poor and face considerable limitations in their farming practices. Nevertheless, they strive to improve their livelihoods despite the myriad constraints they face. They have small sized plots for their household food security. The farmers tend to favour staple foods for their survival rather than cash crops as they focus mainly on subsistence farming. A major constraint is the fertility status of the soils which are cultivated every year with little or no replenishment in terms of fertilizer enrichment. Even though most of the farmers use inorganic fertilizers, the quantities applied are usually too small to have a pronounced effect on their yields.

The effect of rainfall variability on the length of the crop growing period (LGP) over the past three decades was analysed. Data from five meteorological stations in the central region of Malawi, where 90% of the economic activities are agro-based, were analysed. The analysis showed significant changes in the onset, cessation and length of the growing period. There is a clear delayed onset and advanced cessation, and thus a shorter LGP, in most locations with time within the period considered (1980 to 2009). Since farmers are willing to learn and adapt to the effects of climate change, so that their livelihoods can improve and not greatly impacted, the results of this analysis and the consequent recommendation for introducing crop cultivars with a shorter growing cycle, may be useful to farmers.

Next, a calibrated and validated crop growth model, AquaCrop, was used in this research to analyse crop yield gaps and to generate crop management strategies to improve and stabilize crop yields. The multi-crop water productivity model AquaCrop was developed by the Food and Agriculture Organization of the United Nations (FAO) to address food security and assess crop production influenced by environment and management.

Two, field experiments with maize and sorghum were set up during three successive growing seasons (2010/11, 2011/12 and 2012/13), both at Bunda (Lilongwe ADD) and Kasinthula (Shire Valley ADD) to (i) evaluate the effect of fertility levels on rainfed crop yield and (ii) obtain field data for fine tuning and validation of AquaCrop for Malawian conditions. The field experiments had two levels of fertiliser application: full dose (F1) and half dose (F0) according to the recommendations of the government extension service. Also the effect of different crop varieties (early, medium and late maturing) were studied in some of the years. As expected, there was a significant increase in yield of maize and sorghum with higher fertilizer application. The experimental data of the F1 treatments from 2010/11 were used for fine-tuning the AquaCrop model to the environmental conditions in Malawi. The F0 treatments were used for calibrating the soil fertility stress module of the model. For model validation, data from 2011/12 and 2012/13 were used. Different statistical indicators (correlation coefficient r^2, relative root mean square error RRMSE and Nash-Sutcliffe model efficiency EF) showed that the model performed excellent in simulating biomass, soil water content, canopy cover and grain yield of maize and sorghum. It was concluded that AquaCrop was successfully calibrated and validated for maize and sorghum for Malawi and that the model can be used for formulating and evaluating different strategies and their effects on crop production.

AquaCrop was subsequently used to assess the yield stability for maize and sorghum for the current weather conditions in the region. The simulations were run for the two study sites and for three fertility levels (i.e., F1 and F0 as considered in the field experiments, FM as applied in farmers' fields, which implicates a much lower fertility level). Crop yields under FM are between 1.9 to 3.0 ton ha^{-1} for maize and 2.0 to 2.3 ton ha^{-1} for sorghum, which is higher than what is reported by the government studies (1-2 ton ha^{-1}). This is due to the absence of the effect of pests, diseases and weed infestation in the simulations with AquaCrop. With full soil fertility (F1), the production can be doubled. Yet, while very good yields can be expected in good rainy years, the crop yield will be lower than under FM strategies in the drier years. Under all management strategies, the occurrence of failure years is relatively high, i.e. almost 1 year out of 10 years for Bunda and 2 years out of 10 years for Kasinthula.

To study the effect of climate change on cereal production, local-scale climate projections for the future were generated for central Malawi. Climatic change factors from 15 global climate models (GCMs) from the Coupled Model Intercomparison Project phase 3 (CMIP3) were used. The GCM output was downscaled to local-scale future data following two distinct methodologies, i.e. the self-organising maps (SOM) approach by the University of Cape Town-Climate Systems Analysis Group (UCT-CSAG) versus the stochastic weather generator LARS-WG. Finally, the future climatic data generated by LARS-WG were used to assess the effect of climate change on cereal production.

The effects of future climate change on maize and sorghum yields at Bunda were assessed by use of the AquaCrop model the mid-21st century (SRES scenarios A1B). Significant differences in mean yield as compared to the baseline were found. Maize will be impacted negatively while sorghum will benefit from climate change. The projected rather small yield decline of about 5% for maize and the yield increase of 2% to 10% for sorghum contradict the often projected sharp decline of cereals in Southern Africa. Given inconsistencies found between the simulated yields under observed versus generated baseline weather data by LARS-WG, the yield decline of maize might be somewhat larger and the yield increase of sorghum might be slightly smaller. Finally, it has to be noted that despite the small increase or decrease of yield, the occurrence of failure years will almost double from 0.7 year out of 10, to 1.2 years out of 10 with climate change for both maize and sorghum.

Nederlandstalige samenvatting

Voedselonzekerheid blijft een chronisch probleem in zuidelijk Afrika, en in het bijzonder in de regio van de zogenoemde Southern African Development Community (SADC). In die regio worden elk jaar voedseltekorten gemeld, vooral in landen als Malawi, Swaziland en Zimbabwe. In dit onderzoek werd Malawi geselecteerd als casestudy om na te gaan hoe duurzame en betere graanproductie onder regengevoede omstandigheden kan worden bereikt door verhoging van de waterproductiviteit van graangewassen. Het onderzoek richtte zich op twee van de belangrijkste graangewassen in Malawi: maïs, het belangrijkste voedselgewas, en sorghum, een droogtetolerant gewas dat kan overleven onder ongunstige klimatologische omstandigheden.

Slechte weersomstandigheden in combinatie met een hoge bevolkingsgroei en lage bodemvruchtbaarheid liggen aan de basis van verslechterende voedselzekerheid in Malawi. Hoewel irrigatie de landbouwproductie kan verbeteren, wordt het potentieel onderbenut. Regengevoede landbouw domineert nog steeds in Malawi, waardoor graanproductie alleen mogelijk is tijdens het regenseizoen van november tot april. De meeste bodems zijn bovendien sterk verweerd en vereisen regelmatige maatregelen om de bodemvruchtbaarheid te verbeteren. Hoewel potentiële gewasopbrengsten relatief hoog zijn, is de werkelijke gemiddelde opbrengst van kleinschalige landbouw voor de voorbije 10 seizoenen slechts 1,6 ton per hectare voor maïs en 0,7 ton per hectare voor sorghum. Om regengevoede landbouw een zekere bron van voedsel en levensonderhoud te maken voor lokale boeren, moet de kloof tussen potentiële en werkelijke opbrengsten verkleinen.

Dit onderzoek vertrok vanuit een analyse van de sociaaleconomische kenmerken van de kleine boeren in de regio. 60 huishoudens in de Lilongwe en Shire Valley LandbouwOntwikkelingsAfdelingen (LOAs), wiens belangrijkste gewassen maïs en sorghum zijn, werden bevraagd. De LOAs werden geselecteerd als representatieve casestudy's met verschillende klimatologische karakteristieken en landbouwbeheerspraktijken. De resultaten tonen dat de kleine boeren arm zijn en te kampen hebben met aanzienlijke beperkingen in hun landbouwpraktijken. Toch streven ze ernaar om hun bestaansmiddelen te verbeteren, ondanks de talloze beperkingen waarmee ze worden geconfronteerd. Boeren hebben doorgaans kleine percelen om voedselzekerheid te garanderen voor hun huishouden. Zelfvoorzienende landbouw primeert: boeren hebben eerder de neiging om basisvoedsel voor hun overleving te telen dan marktgewassen om te verhandelen. Hun voornaamste beperking daarvoor is de bodemvruchtbaarheid, omdat landbouwgronden jaar in jaar uit met weinig of geen meststof verbouwd worden. Hoewel de meeste boeren wel anorganische meststoffen gebruiken, zijn de gebruikte hoeveelheden meestal te klein om een uitgesproken effect op de opbrengst te hebben.

Ten tweede werd het effect van neerslagvariabiliteit op de lengte van het groeiseizoen in de voorbije drie decennia geanalyseerd. Gegevens van vijf meteorologische stations in de centrale regio van Malawi, waar 90% van de economische activiteiten landbouwgerelateerd zijn, werden geanalyseerd. De analyse legde significante veranderingen in de start, het einde en de lengte van het groeiseizoen bloot. Er is duidelijk een latere start en een vervroegd einde, en bijgevolg een kortere duur van het groeiseizoen doorheen de tijd binnen de periode 1980-2009. De resultaten suggereren de invoering van alternatieve gewasvariëteiten met een kortere groeicyclus als adaptatiemaatregel. Dit is een belangrijke conclusie, want boeren blijken immers bereid te zijn om te leren en zich aan te passen aan de gevolgen van de klimaatverandering om beter in hun levensonderhoud te voorzien en zo weinig mogelijk door de klimaatverandering beïnvloed te worden.

Vervolgens werd in dit onderzoek een gewasmodel, AquaCrop, gebruikt om de oorzaken van lage gewasopbrengsten te analyseren en beheerstrategieën die leiden tot verbetering en stabilisering van de gewasopbrengst te genereren. Daarvoor werd het multi-gewas model gekalibreerd en gevalideerd voor de regio. Het waterproductiviteitsmodel AquaCrop werd door de Voedsel- en Landbouworganisatie van de Verenigde Naties (FAO) ontwikkeld om de voedselzekerheidsproblematiek aan te pakken en gewasproductie zoals beïnvloed door omgevingsfactoren te evalueren.

Veldexperimenten met maïs en sorghum worden opgezet in drie opeenvolgende groeiseizoenen (2010 / 11, 2011/12 en 2012/13) in Bunda (Lilongwe) en in Kasinthula (Shire Valley) om (i) het effect van verschillende bodemvruchtbaarheidniveaus op regengevoede gewasopbrengst te evalueren en (ii) veldgegevens te verzamelen voor de lokale ijking en validatie van het AquaCrop model. De experimenten kenden twee niveaus van bemesting: volledige dosis (F1) en halve dosis (F0) volgens de aanbevelingen van de overheid. Ook het effect van verschillende variëteiten (vroege, gemiddelde en late rijping) werden onderzocht in enkele jaren. De experimenten toonden zoals verwacht een aanzienlijke toename in maïs en sorghum opbrengst met hogere meststoffen. De experimentele gegevens van de F1-behandelingen van het 2010/11 groeiseizoen werden gebruikt voor de ijking van AquaCrop. De F0 behandelingen werden gebruikt om de bodemvruchtbaarheidmodule van het model te ijken. De experimentele gegevens van de overige seizoenen werden gebruikt voor validatie. Verschillende statistische parameters (correlatiecoëfficiënt r^2, kwadratisch gemiddelde fout RRMSE en Nash-Sutcliffe modelefficiëntie EF) bevestigden goede simulaties van biomassa, bodemvochtgehalte, gewasbedekkingsgraad en oogst van maïs en sorghum voor zowel de kalibratie- als de validatiegegevens. Daaruit werd geconcludeerd dat het model succesvol is geijkt en gevalideerd voor maïs en sorghum voor in Malawi, en gebruikt kan worden om verschillende beheerstrategieën en hun effecten op gewasproductie te formuleren en evalueren.

AquaCrop werd vervolgens gebruikt om de opbrengststabiliteit van maïs en sorghum voor de huidige weersomstandigheden in de regio te beoordelen. Simulaties werden uitgevoerd voor de twee studielocaties en drie bodemvruchtbaarheidniveaus (F1 en F0 zoals in de veldproeven, en FM volgens de lokale gebruiken van landbouwers wat een veel lager vruchtbaarheidniveau inhoudt). Gesimuleerde gewasopbrengsten voor FM van 1,9-3,0 ton per hectare voor maïs en 2,0-2,3 ton per hectare voor sorghum zijn hoger dan de oogsten uit overheidsstudies (1-2 ton per hectare). Dit is te wijten aan de afwezigheid van het effect van plagen, ziekten en onkruid in de simulaties van AquaCrop. De simulaties tonen dat met volledige bodemvruchtbaarheid (F1) de productie gemakkelijk verdubbeld kan worden. Zeer goede opbrengsten kunnen worden verwacht in jaren met veel regen, maar de gewasopbrengst is wel lager dan bij FM in drogere jaren. Voor alle beheerstrategien zijn jaren zonder oogstopbrengst hoog: bijna 1 jaar in 10 voor Bunda en 2 jaar in 10 voor Kasinthula.

Om het effect van klimaatverandering op de graanproductie te bestuderen, werden lokale klimaatgegevens voor de toekomst gegenereerd voor centraal Malawi. Hiervoor werden klimaatsignalen van 15 globale klimaatmodellen (GCMs) van het Coupled Model Intercomparison Project fase 3 (CMIP3) gebruikt. De GCM-output werd neergeschaald naar lokale weersgegevens met behulp van twee verschillende methodes: zelforganiserende kaarten van de University of Cape Town-Climate Systems Analysis Group (UCT-CSAG) versus een weersgenerator (Lars-WG). De klimaatgegevens verkregen met behulp van de laatste methode werden uiteindelijk gebruikt om het effect van klimaatverandering op de graanproductie in te schatten.

De effecten van de klimaatverandering op maïs en sorghum productie in Bunda worden bestudeerd met behulp van AquaCrop voor het midden van de 21e eeuw (SRES scenario A1B). In vergelijking met de historische baseline periode zijn er significante verschillen in gemiddelde opbrengst.. Maïs zal negatief worden beïnvloed, terwijl sorghum zal profiteren van de klimaatverandering. De voorspelde kleine opbrengstdaling van ongeveer 5% voor maïs en de opbrengststijging van 2% tot 10% voor sorghum is in tegenspraak met de vaak verwachte scherpe daling van graanoogsten in Zuidelijk Afrika. Gezien er enige inconsistentie bestond tussen de gesimuleerde oogst met historische geobserveerde versus gegenereerde weersgegevens met behulp van LARS-WG, zou de opbrengstdaling van maïs groter kunnen zijn en de opbrengsttoename van sorghum kleiner. Tenslotte moet worden opgemerkt dat ondanks de kleine toename of afname van de opbrengst, het voorkomen van oogstmislukkingen bijna verdubbelt door de klimaatverandering.

List of Figures

List of Tables

List of acronyms

[CO2]	Concentration of carbon dioxide in the atmosphere
ADD	Agricultural Development Division
AEDC	Agricultural Extension Development Coordinator
AEDO	Agricultural Extension Development Officer
AEZ	Agro-ecological zone
AGRYHMET	Centre Regional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle
ANOVA	Analysis of variance
APSIM	Agricultural Production Systems Simulator
BCM2	Bjerknes Centre for Climate Research
CC	Canopy Cover
CC*	Maximum canopy cover
CERES	Crop Environmental REsources Synthesis
CGMR	Canadian Centre for Climate Modelling and Analysis
CMIP3	Coupled Model Intercomparison Project phase 3
CNCM3	Centre National de Recherches Meteorologiques
CropSyst	Cropping Systems simulation model
CSMK3	Commonwealth Scientific and Industrial Research Organisation
CV	Coefficient of variation
DAP	Days after planting
DoI-MoAFS	Department of Irrigation-Ministry of Agriculture and Food Security
DSSAT	Decision Support System for Agrotechnology Transfer
EF	Nash-Sutcliffe model efficiency
ENSO	El Nino Southern Oscillation
EPA	Extension Planning Area
EPIC	Erosion Productivity Impact Calculator
ET_a	Actual evapotranspiration
ET_c	crop evapotransipiration
ET_o	Reference evapotranspiration

F0	Half recommended fertilizer application rate
F1	Full recommended fertilizer application rate
FAO	Food and agricultural Organisation of the United Nations
FC	Field Capacity
FGOALS	Institute of Atmospheric Physics
FM	Farmers field management practices
GCM	Global Circulation Models
GDD	Growing degree days
GDP	Gross Domestic Product
GFCM21	Geophysical Fluid Dynamics Laboratory
GIAOM	Goddard Institute for Space Studies
GoM	Government of Malawi
HDI	Human Development Index
HIV/AIDS	Human immunodeficiency virus infection/acquired deficiency syndrome
Inet	Net irrigation requirement
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
Kc	crop coefficient
KS	Kolmogorov-Smirnov test
Ks	stress coefficient
Ksat	saturated hydraulic conductivity
LARS-WG	Laws and ashton research science-weather generator
LGP	Length of Growing Period
LSD	least squared difference
LUANAR	Lilongwe University of Agriculture and Natural Resources
masl	meters above sea level
MK	Mann-Kendall statistic
MoAFS	Ministry of Agriculture and Food Security
NDVI	Normalized Difference Vegetation Index
NGO	Non-Governmental Organisation

NSO	National Statistics Office
OM	organic matter
PWP	Permanent Wilting Point
r^2	Person's correlation coefficient
RCBD	Randomised Complete Block Design
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RDP	Rural Development Programme
RRMSE	Relative Root Mean Square
SADC	Southern African Development community
SAT	saturation point
SOM	Self-Organising Maps
SRES	Special Report on Emissions Scenarios
SSA	Sub-Saharan Africa
SWC	Soil Water Content
TAW	Total Available Water
UCT-CSAG	University of Cape Town-Climate Systems Analysis Group
UNDP	United Nations Development Programme
WMO	World Meteorological Organisation
WOFOST	WOrld FOod STudies simulation model
WP*	Water Productivity
Y	Grain yield
Zr	root zone depletion

Table of Contents

Part I Introduction

Chapter 1
Problem statement and research questions

1.1 Problem Setting: Food insecurity, the need for increased crop production

Food insecurity still remains a challenge even though global food production has been rising (Pretty et al., 2003). Projections of global population suggest that there is a need to increase food production by 70%, in order to support the projected population of 9.5 billion people by the year 2050 (IPCC, 2014). The need to increase food production is not only related to the increasing population, but also to the growth in per capita consumption as welfare of people is improving. Hence the demand for more nutritious diets is rising, and consequently the demand for food is even growing faster than population (Cook et al., 2006). In order to meet increased food demand in the face of climate change, there is need to develop innovative approaches to adaptation (Bharwani et al., 2005). However, projections of crop impacts are diverse, with yield impacts ranging from -98% to +16% across Africa depending on crop, region, and climate scenario (Nordhagen and Pascual, 2013). For Sub-Saharan Africa (SSA) most predictions suggest that the vast majority of farmers will suffer agricultural losses, especially due to a higher frequency, intensity, and magnitude of extreme events (Fischer et al., 2005; Kurukulasuriya and Mendelsohn, 2008; Schlenker and Lobell, 2010; Schmidhuber and Tubiello, 2007; Slingo et al., 2005). While SSA has been identified as one of the region's most vulnerable to the impacts of climate change (Challinor et al., 2007), the changes that will have the greatest impact on crop production will occur at field level, for which climate model simulations are unavailable (Nordhagen and Pascual, 2013). The farming techniques in SSA are still relatively traditional, cultivation mostly rainfed and the agricultural landscape dominated by smallholder farmers that have very limited capacity to adapt (Mueller et al., 2011). Therefore, successful adaptation to climate change and improvement of the food production in the region will be complicated. This can be achieved through a combination of strategies. Among numerous strategies, there are two major ways which are effective and fitting to smallholder farmers. These are adopting efficient crop management practices and improving crop water productivity.

1.1.1 Efficient crop management practices

Rainfed agriculture which accounts for around 60% of production in developing countries depends entirely on rainfall stored in the soil profile, hence its vulnerability to increasing rainfall variability (Porter et al., 2014). In a global perspective, the agricultural productivity in rainfed areas is lower with grain yields averaging 1.5 t ha^{-1} for smallholder and resource-poor farmers and often exceeding 5-6 t ha^{-1} for commercial rainfed agricultural systems in developing countries (Rosegrant et al., 2013). These observations suggest that the apparent biophysical constraints causing low yields in the developing countries might be overcome by appropriate crop management practices (Rockström et al., 2010). Therefore, agriculture policies and investments will need to become much more strategic in these countries. They will have to unlock the potential of agricultural water management practices to raise productivity, spread equitable access to water and conserve the natural productivity of the water resource base (FAO, 2003).

1.1.2 Improving crop water productivity

In the context of a changing climate and a growing population, there is high competition for water. It is therefore unlikely that the agricultural sector, which today claims 70% of the total fresh water resources (FAO, 2003), can secure a larger share of the already highly exploited fresh water resources (FAO, 2003). Increasing the productivity of water in agriculture to sustain and improve food security for the coming generations is the best possible option available (Kijne et al., 2003). This drives the demand to produce enough food for future generations with the same or less water than is presently available to agriculture. Therefore, there is a need to increase water productivity (unit of product produced per unit of water evapotranspired) without compromising food security (Kijne et al., 2003). It entails getting more units from a single drop of water. This strategy is popularly known as: more crop per drop (Kijne et al., 2003). Either water can be saved for other uses while maintaining food production, or the food production can be increased with the same amount of water (Kijne et al., 2003). The increasing water scarcity resulting from population growth, rising incomes, and climate change, limits the amount of water available for food production and threatens food security in many countries (Cook et al., 2006). The need to improve the efficiency of water use in crop production is never more obvious (Hsiao et al., 2009). Proper allocation of water resources is the solution to this apparent water crisis. However, for developing countries, which rely heavily on rainfall for food production, allocating the diminishing water resources to agriculture and other water users is a major problem (FAO, 2003).

1.2 Crop models as tools for planning and decision making

Continued pressure on agriculture, food insecurity and adaptation to climate change have made integrated assessment and modelling of agro-ecosystems development increasingly important to enable the analysis of multiple scenarios. Various modelling tools are used to support decision making and planning in agriculture. Crop models integrate different factors influencing crop production and contribute to understanding of their interactions. Efficient long-term assessments of numerous scenarios for both historical and future climatic conditions are possible with the use of models (Boote et al., 1996; Tubiello and Ewert, 2002). However, it is worth mentioning that the models often require detailed information to operate at field scale. Since field experiments tend to be laborious, time and resource consuming with results depending on experiment set-up, a combination of field experiments and improved biophysical model structure would contribute positively to the success of increasing agricultural productivity even in rainfed smallholder systems.

To address food security and assess crop production influenced by environment and management, numerous crop simulation models were developed over the last four decades. Some examples include DSSAT (Jones et al., 2003b); CERES, EPIC (Williams et al., 1989); CropSyst (Stockle et al., 1994); APSIM (Holzworth et al., 2014; Keating et al., 2003). These models often require a large number of input variables and parameter values that are not easily available for the diverse range of crops and environment worldwide. Furthermore, these models have complex computation schemes, which is a strong constraint for extension services practitioners, consulting engineers, governmental agencies, NGOs and farmers associations. Generally, the scientists are well-versed with the equations, variables and parameters more than models' end users.

As a contribution to solving these limitations of the existing crop models, the Food and Agriculture Organization of the United Nations (FAO) has developed AquaCrop (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009; Vanuytrecht et al., 2014a), a multi-crop water productivity model that seeks a balance between simplicity, accuracy and robustness. Its calculation scheme is transparent even though based on fundamental biophysical processes, to ensure realistic simulation of crop responses to environment. To facilitate wide application, this multi-crop water productivity model requires a relatively small number of explicit parameter values and mostly intuitive input variables, which are obtainable by straightforward methods. It simulates crop development and production under a wide range of environmental and management conditions, based on user-specified inputs of daily climatic data (rainfall, minimum and maximum temperature and reference evapotranspiration (ET_0)), soil physical characteristics (total available soil water content and saturated hydraulic conductivity), crop characteristics (crop phenology for the local cropping environment), and irrigation and field management information. It was for these reasons that the AquaCrop model was chosen for this research. The model has been successfully calibrated and evaluated for several common crops including barley, maize, wheat, tef, quinoa, and cotton (Abrha et al., 2012; García-Vila et al., 2009; Geerts et al., 2010; Geerts et al., 2009; Tsegay et al., 2012). A calibrated and validated AquaCrop model can be used to analyse crop yield deficits and generate crop management strategies to improve and stabilize crop yields.

1.3 Case study: Cereal production in Malawi

Food insecurity continues to be a chronic problem in Southern Africa and particularly in the Southern African Development Community (SADC) region. Across the region food shortages are reported every year especially in countries including Lesotho, Malawi, Swaziland and Zimbabwe. According to the SADC Regional Vulnerability Assessment report (SADC, 2013), an estimated 14 million people out of a total population of 277 million were food insecure. This indicates that SADC is facing a silent food insecurity emergency (OCHA, 2012). In this thesis, Malawi as one of the member states of SADC and affected by food insecurity, has been selected as a study case on possible effects of climate variability and climate change on cereal production.

Like most of the countries in SADC, Malawi relies heavily on rainfed agriculture for food production. This makes domestic food availability and the economy as a whole highly vulnerable to climatic variation. Since 1990, Malawi has experienced severe food shortages in 1992, 1994, 1997, 2001, 2002 and 2006 precipitated by drought or heavy rains (GOM, 2007). Poor weather conditions coupled with high population growth and low soil fertility are believed to be major contributory factors to deteriorating food security in Malawi (GOM, 2007).

Under normal circumstances, Malawi produces about 1.7 million tons of maize to feed itself (Pauw et al., 2010). Of late, there has been a declining trend of this production resulting in increasing food insecurity. A wide yield gap exists between the actual and the potential yields of rainfed maize (central region) and sorghum (southern region) of smallholder farming. According to FAO (2012b), the production of maize has been fluctuating around an average of 1.2 t ha^{-1}, and sorghum around 0.6 t ha^{-1}. This is the result of several factors including changes in climatic (long dry spells, erratic and unreliable rainfall), reduction of arable land, population growth (with the population estimated to be 13.1 million with a growth rate of about 2.8% (NSO, 2008)), high incidence of HIV/AIDS which has drained the agricultural labour, low soil fertility, and water stress. To make rainfed agriculture the main source of food and livelihood security for rural communities, the yield gap must be reduced (Kahinda et al., 2007). Hence addressing this problem was one of the goals of this thesis.

Besides maize, which is an important staple food crop in Malawi, also sorghum is subject of this thesis. Sorghum has been grown in Malawi on a very small scale. Recently, the promotion of sorghum has risen as it is considered an important staple food crop for certain parts in Malawi (e.g. Shire valley). It is now being regarded as a food security crop besides being a drought tolerant crop in Malawi. Sorghum has shown great potential as a food crop particularly in east Africa (Wortmann et al., 2009) where it is extensively cultivated. In climates which can be considered too dry for maize, sorghum has responded favourably. It copes well with annual rainfall ranging from 350 to 750 mm and also tolerates a wide array of soils and below-optimal soil fertility (Wenzel, 2003). Unlike maize, which has been the focus of modelling for decades (Hsiao et al., 2009) sorghum has not been extensively researched in terms of its productivity in Malawi. Worse still, there is hardly recent published research literature on sorghum modelling for Malawi. Recent research on sorghum in Malawi has dwelt much on phytopathology and gene improvement but not on yield production and adaptability to different climates. Yet, sorghum is remarkably drought-resistant and vitally ideal for food security. This indicates the existing knowledge gap about sorghum in Malawi. Research on its applicability to non-traditional environments is therefore required to get an insight on how important sorghum can be to the nation of Malawi, especially with the present changing and uncertain future climate.

With little resilience to climatic changes, economic and social shocks, smallholder farmers have become extremely vulnerable to food insecurity. Climate change increases the uncertainty as most of the households are unaware of the fast changing environment. This motivated this research to add a focus on possible effects of climate change on cereal production. Climate change has been an intensive area of research in the recent years. However, there has been relatively little work published on the impacts of future climate change scenarios on cereal production in Malawi. Climatic studies which focus on regional analysis for southern Africa predict a warmer and drier climate for the region (IPCC, 2007; Stainforth et al., 2005; Thornton et al., 2006). This implies a possible yield reduction if the current trend of management practices and crop water productivity continues without adaptation.

Following the recent changes in climate, (i.e. increasing temperatures, altered rainfall patterns, unreliable and erratic rainfall), cereal production in Malawi is facing various challenges. Production of maize and sorghum by smallholder farmers can be increased through proper and evaluated management practices as well as improving crop water productivity. Molden et al. (2010) states that a much stronger impact on crop yield is believed to come from crop management and improving crop water productivity. This research focuses on central and southern Malawi, the major cultivation areas of the selected crops of study, to evaluate the practicability of different management options which are relevant for boosting food production in the current and projected future climate.

1.4 Research questions and objectives

The main objective of this research is to evaluate sustainable management for stabilizing and increasing cereal yield production of small-scale farmers in Malawi in current and future climatic conditions. To meet this objective, the following research questions and associated scientific queries are addressed.

Research questions:

1. What has been the trend of rainfall in the past three decades in Malawi and its effects on the length of growing period?

2. What are the future climate change projections for Malawi for the 2050's?

3. Is AquaCrop capable of simulating crop growth and development on soils with different fertility levels for maize (*Zea mays* L.) and sorghum (Sorghum *bicolor* L. Moech) in two contrasting climates in Malawi?

4. What is the potential impact of future climate change for the 2050s on crop production in Malawi?

Scientific queries:
1. Assessment of historical climatic trends and its relation to crops' growing seasons
2. Development of future climate change scenarios for the 2050s
3. Fine-tuning and validation of a crop model to model crop responses, with inclusion of practical management practices that are characteristic of a small-scale and resource poor farmers' environment
4. Application of the model for climate change impact assessment on crop production for different cereals in Malawi

1.5 Thesis outline

This dissertation is compiled of five main parts. The parts are schematically presented in Figure 1-1 and described as follows:

Part I introduces the research in a broad context, the motivation behind the research, the general methodology, the research questions and the main objectives.

Part II is the environment section, where research questions 1 and 2 are tackled.
- Chapter 2 describes the study area characteristics (soil, historical climate, major crops cultivated and local management practices).
- Chapter 3 describes the socio-economic status of the target group for this research, the "*smallholder farmers*". A socio-economic survey was conducted in two locations to find out the characteristics of the smallholder farmers, their needs and how they do their farming in the areas. This information was essential for this research, so as to come up with management strategies tailored to the target group. This is the only way the results will be meaningful to the end users.
- Chapter 4 describes the effect of historical rainfall variability on the length of the crop growing period over the past three decades. Central Malawi was used as a case study in this research. This information is essential for smallholder farmers, so that they can identify the best crop cultivars that can do well with the reported changes in the length of growing season.
- Chapter 5 describes the long process of future climate change data generation that was followed in this research. This was necessary as it provided inputs to help address research question 4. Local-scale climate projections for central Malawi were generated for the middle of the 21st century (2046-2065) by considering up to 15 GCM's and the A1B emission scenario.

Part III is the model section where research question 3 is addressed. This is done through fine-tuning of AquaCrop against field experiments conducted in two contrasting environments for both maize and sorghum.

- Field experiments were set up in 3 successive growing seasons in Bunda and Kasinthula with various levels of soil fertility and water stress (Chapter 6).
- The field experiments results aided in fine-tuning and validating AquaCrop to local Malawi conditions (Chapter 7)

Part IV is the simulation and assessment section. It tackles research question 4. It presents the impact assessment of future climate change for 2050s on cereal yield production in central Malawi. The simulation of future cereal yields was conducted using the validated AquaCrop model (Chapter 7). With the calibrated AquaCrop model, crop yields for maize and sorghum, under rainfed conditions, and with various levels of soil fertility were simulated in contrasting environments in Malawi, and this for actual (Chapter 8) and future (Chapter 9) climatic conditions.

Part V is the conclusion section where the main findings of the research are presented and future research prospects are proposed.

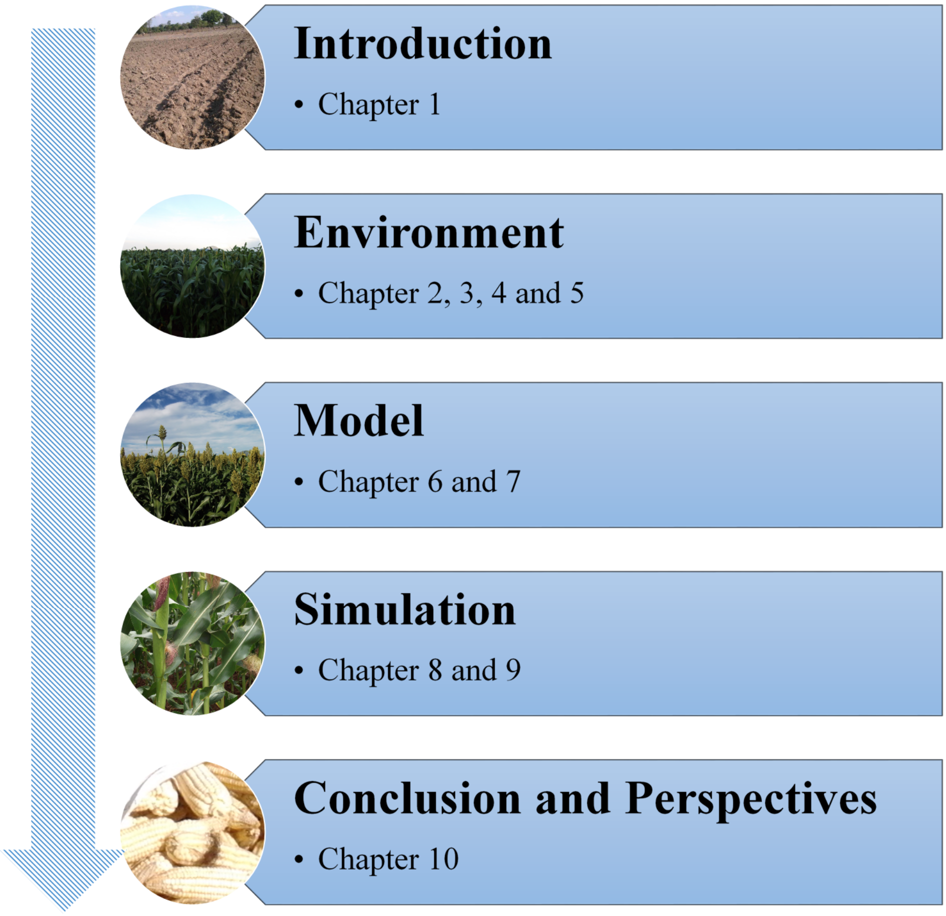

Figure 1-1: Outline of the dissertation

Part II Environment

Chapter 2
Study area

2.1 Introduction

This chapter presents a description of the study area. The location, followed by a brief overview of Malawi's agriculture set up, is introduced first. The climate, soil and main cereal crops grown in the study area are presented. Lastly it concludes with the detailed description of two crops which were used in this research.

2.2 Location and overview of Malawi's agriculture

2.2.1 Location

Malawi lies south of the Equator between latitudes 9° 30'S and 17°S and longitudes 33°E and 36°E. It is boarded by Zambia to the northwest, Tanzania to the northeast and Mozambique on the east, south and west (Figure 2-1). The total land area is 118, 484 km^2, 20% of which is under water in the form of lakes. Malawi is one of the poorest countries in the world. It has a Gini coefficient of 46.2% (World Bank, 2010) and Human Development Index (HDI) of 0.414 (UNDP, 2014). These indices confirms the status of population of Malawi. It means a minority of people are in control of economic activities.

The experiments in this study were conducted in two sites: in central and southern regions of Malawi. In the central region, the study was conducted at Lilongwe University of Agriculture and Natural Resources (LUANAR), Bunda College Campus (latitude 14° 11'S, longitude 33° 'E, altitude 1174 meters above sea level (masl)). In southern Malawi, the study was conducted at Kasinthula research station (latitude 16° 5'S, longitude 34° 49'E, altitude 80 masl) in the floor of the African Great Rift Valley (Fandika et al., 2007). The locations of the research sites are shown in Figure 2-1.

Figure 2-1: Map of Africa, with an inset of Malawi map showing agricultural administrative divisions and the two experimental sites of this study

2.2.2 Overview of Malawi's agriculture

Agriculture is the most important sector of the Malawian economy. Depending on climatic conditions, the sector accounts for about 40% of the Gross Domestic Product (GDP) (MoAFS, 2012). It contributes about 75% of the country's export earnings and generates income for around 84% of the population (NSO, 2008). It is estimated that Malawi has 4.7 million hectares of arable land can be cultivated under rainfed or irrigated agriculture (MoAFS, 2012). However it is estimated that only 2.5 million hectares are under cultivation. The agricultural sector is characterised by a dualistic structure; small-scale and estate sub sectors with the former cultivating 70% of the land (MoAFS, 2012). The smallholder farmers are important players in the sector as they are involved in production of food crops such as cereals, legumes and pulses.

Although irrigation has the potential to increase agricultural productivity, it is not fully utilised in Malawi. This is due to its expensive requirements in terms of installation as well as operation and maintenance costs. Malawi has an irrigation potential of 630,000 ha of which only 14% (112,000 ha) in under irrigation (DoI-MoAFS, 1992; MoAFS, 2012). Rainfed agriculture still dominates Malawi's agriculture as it covers about 99% of agriculture. This situation makes food production very seasonal and expose the country to food insecurity situations in off season months (MoAFS, 2012).

Agricultural administration is done through the Agricultural Development Divisions (ADDs). These are administrative divisions within the agricultural extension department under the ministry of agriculture and food security. The country is divided into eight ADDs. These are Blantyre, Karonga, Kasungu, Lilongwe, Machinga, Mzuzu, Salima and Shire Valley (Figure 2-1). The ADDs were divided following different agro-ecological zones within the country. The characteristics of the agro-ecological zones are presented in Table 1-1.The District Agricultural Development Offices (DADO) (previously known as Rural Development Projects (RDP)) are subdivisions within the ADDs providing operational support services at the grass-roots level under the National Rural Development Programme instituted in 1978 to promote smallholder agriculture (MoAFS, 2012). The DADOs are further subdivided into Extension Planning Areas (EPA). It is from these EPAs that extension expertise and new technologies in Malawi's agriculture trickle down to smallholder farmers.

Table 2-1: Characteristics of agro-ecological zones of Malawi (Source; Wiyo, 1999: MoAFS, 2012)

AEZ	**Altitude Range (masl)**	**Temperature Mean (°C)**	**Major Soil Group[a]**	**Rainfall Range (mm)**	**ADD**
Highlands	1600 - 3000	10 - 26	Lithic Leptosols, Regosols	1600 - 2200	Mzuzu, Karonga, Blantyre
Plateau	900 - 1600	16 - 26	Ferrasols, Luvisols, Lixisols	900 - 1400	Lilongwe, Kasungu
Rift Valley Escarpment	600 - 1500	14 - 24	Lithic Leptosols	900 - 1200	Blantyre, Mzuzu
Lakeshore Plains	300 - 600	20 - 29	Gleysols, Vertisols, Fluvisols	800 - 1100	Karonga, Mzuzu, Salima, Machinga
Lower Shire Plains	33 - 300	21 - 33	Gleysols, Vertisols, Fluvisols	< 800	Shire Valley

[a] = FAO/UNESCO classification; AEZ = agricultural ecological zone; masl = metres above sea level

2.3 Climate

Malawi has a sub-tropical climate which is relatively dry and strongly seasonal (Jury and Mwafulirwa, 2002). It is largely influenced by the huge water mass of Lake Malawi, which defines almost two-thirds of Malawi's eastern border. There are two distinct seasons: the rainy season from November to April and the dry season from May to October (Figure 2-3). The dry season may be divided into the cool dry period from May to July and the hot dry period from August to October. Rainfall is unimodal with annual amounts ranging from 700 to 2400 mm with mean annual rainfall being 1180 mm (GoM, 2014). Its distribution is mostly influenced by the topography and proximity to Lake Malawi (Figure 2-2). The main rain bearing system in Malawi is the Inter-Tropical Convergence Zone (ITCZ) (Ngongondo et al., 2011). The ITCZ marks the convergence of the north-easterly monsoon and south-easterly trade winds, and during the rainy season, it oscillates over the country, often connecting with troughs in the Mozambique channel. The other main rain-bearing system for Malawi is the northwest monsoon, composed of recurved tropical Atlantic air that reaches Malawi through the Congo basin (Jury and Mwafulirwa, 2002). This system in conjunction with the ITCZ brings well-distributed rainfall over the country, and floods may be experienced.

Temperatures are greatly influenced by the topography and decrease with increasing altitude. The mean maximum and minimum temperatures are 28°C and 10°C respectively in the plateau areas, and 32°C and 14°C respectively in the rift valley plains (Figure 2-2). The highest temperatures occur in October/November while the lowest temperatures are experienced in June/July (Frenken, 2005). Humidity ranges in order of magnitude of 50% in the drier months of September/October and over 80% in wetter months of January/February (GoM, 2014).

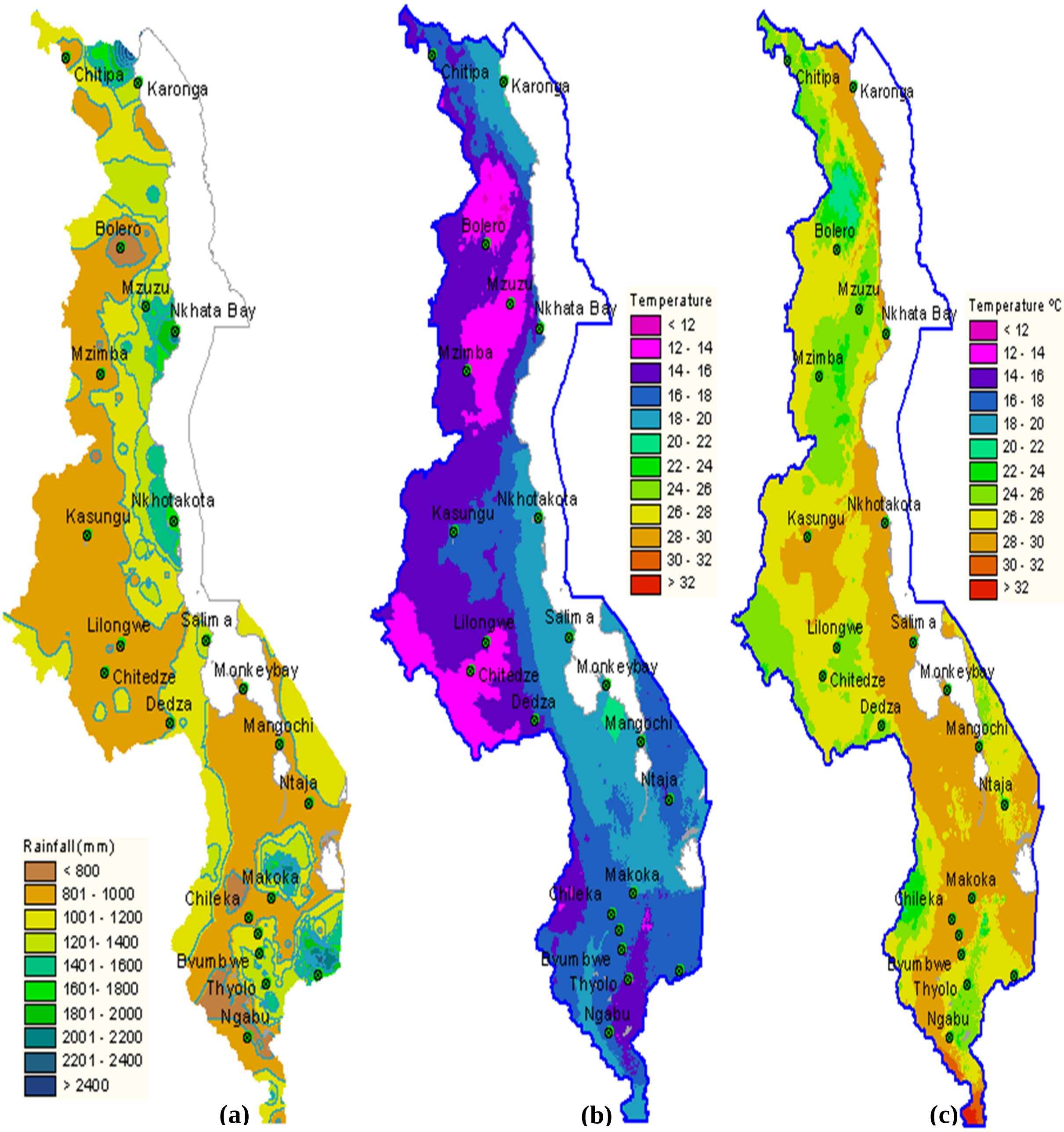

Figure 2-2: Map of Malawi showing spatial distribution of (a) rainfall; (b) minimum air temperature and (c) maximum air temperature. (Source: Department of Climate Change and Meteorological services)

For the two study sites, Bunda is sub-humid and classified as *Cwa* on Köppen climate classification (Peel et al., 2007). Temperature ranges from 16 to 26°C with annual average rainfall between 800 to 1,200 mm. The monthly reference evapotranspiration (ET_o) ranges between 70 mm in winter to a peak of 170 mm in October. Kasinthula is drier than Bunda and classified as *Aw*. Temperature ranges from 18 to 35°C, with annual average rainfall between

500 to 800 mm. The monthly reference evapotranspiration (ET_o) ranges between 100 mm in winter to a peak of 200 mm in October (Figure 2-3).

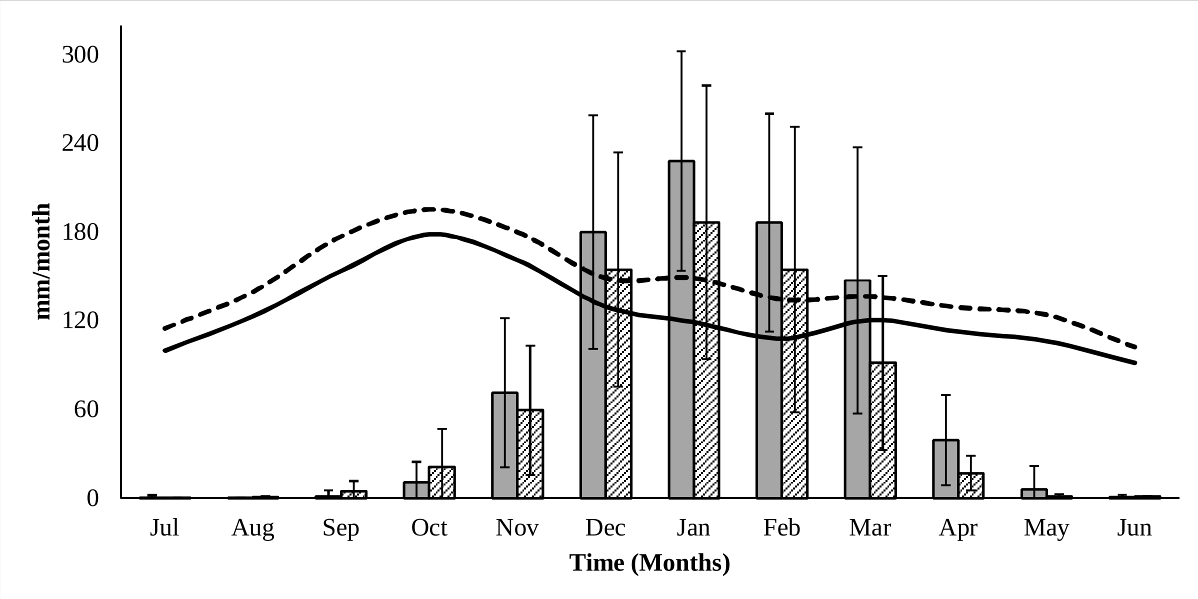

Figure 2-3: Average (1980-2012) monthly rainfall (bars with indication of standard deviation) and reference evapotranspiration (lines) for Bunda (grey bars and continuous line) and Kasinthula (hatched bars and dotted line) (Source: Department of Climate Change and Meteorological Services)

2.4 Soil

The major soils of the study area are presented in Table 2-1. The soils have varying inherent soil fertility depending on their formation. Most of the soils in Malawi are highly weathered hence show the need to enhance their fertility regularly. The soils have low to medium nitrogen (N) to potassium (K) and low calcium (Ca), sulphur (S) and manganese (Mg) but high total phosphorus (P) (FAO, 1995). Zinc (Zn) and Iron (Fe) tend to be average while boron (B), copper (Cu) and molybdenum (Mo) are low with manganese (Mn) being high among the micronutrients (FAO, 1995). Nitrogen is the most limiting factor of all nutrient elements and therefore most of Malawi's soils respond to adding N fertilizers (MoAFS, 2012).

For the experimental sites, Bunda being in the Lilongwe plains has predominantly red soils classified as ferric Luvisol, with a sandy clay texture and deep water tables (>8 m) (Lowole, 1983; Wiyo, 1999). The soil at Kasinthula research station is classified as gleyic Vertisols. It is moderately coarse to moderately fine textured developed in the brown sediments of the lower Shire terrace (Kadyampakeni, 2013). The soil is generally well drained sandy clay loam and the measured water table at the experimental station was deep (>5 m).

2.5 Main cereals and common crop management practices

The climate of Malawi is suitable for the production of a wide range of tropical crops. The main cereals grown include; maize (*Zea mays* L), rice (*Oryza sativa* L), sorghum (*Sorghum bicolor* [L.] Moench), and millet (*Pennisetum glaucum*). In terms of productivity, the average yield of the main cereals are presented in Table 2-2.

Table 2-2: Estimated main cereal productivity in Malawi for the past ten seasons (Source: MoAFS, 2012)

Crop	Production (t)	Cultivated area (ha)	Yield (t ha^{-1})
Maize	2,500,267	1,569,627	1.593
Rice	109,174	61,978	1.761
Sorghum	49,802	69,570	0.716
Millet	8,613	10,646	0.809

Prior to the introduction of maize, sorghum and millet have been the staple foods for Malawi, but their production plummeted due to the changes in government priorities and policies soon after Malawi's independence. The agricultural policy promoted the production of maize hence national food security has mainly been defined in terms of access to maize. Sorghum is an important staple food in the shire valley and a food security crop in other marginal rainfall areas.

These cereals are grown on ridges (Figure 2-4) constructed across the field slope usually using hand hoes (Wiyo et al., 1999). The use of machinery and ox-drawn implements is rare in the smallholder agriculture set up. Ridge size, shape and spacing vary from ridge to ridge and from farm to farm depending on the farmer, local practices and topography. The seeds are sown on planting stations on the ridge at some specified distance apart. Pacing and 'eye' measurements (Wiyo et al., 1999) are often used in locating planting stations. Ridge spacing and alignment is fixed from year to year as ridges become furrows this year and furrows become ridges next year. The advantage of practicing this type of tillage system is that the soil is always well aerated and it allows for moisture conservation and easy root penetration.

Figure 2-4: A picture of ridges from a typical smallholder farmer's field ready for planting (Photo credit: Yamikani Fiwa)

Planting usually takes place at the start of the rainy season (Nov-Dec) with very few farmers applying nutrients. With the fertility levels of the soils in Malawi, the farmers are advised to apply more nutrients either from organic sources or inorganic sources. Fertilizer application is done twice, basal dressing (two weeks after germination) and top dressing after the crops have reached knee high. This is contrary to the advice given by the extension services, which encourages basal dressing at planting and top dressing two to three weeks after germination. The amounts of fertilizer applied are usually measured by hand and applied close to the planting stations. The fertilizer holes are drilled with a pole at around 2-3 cm away from the planting stations and the fertilizer is put into these small pits (2.5 cm deep). The holes are covered with soil after placing the fertilizer. Since inorganic fertilizers are expensive, about 30% of smallholder farmers in Malawi apply it correctly in their fields. Most of the smallholder farmers will only apply fertilizer when they can afford. The crops are harvested after physiological maturity. Some are harvested later depending on the food security of the household.

Maize and sorghum will be discussed in detail, with emphasis only on characteristics relevant for this research.

2.5.1 Maize

Maize ranks as the most important crop worldwide in terms of grain production; in Malawi it is the staple food for the country. It performs best in tropical environments with hybrids being the high-yielding maize cultivars. Malawi has suitable climate for the growth and development of maize. Maize is usually planted in the period between November and December (the start of the rainy season) throughout the country, with southern Malawi being earlier than the northern. It grows rapidly during the high rainfall months of January and February. Maize usually is mature early April and harvested late April or early may. In Malawi rainfall is usually characterised by dry spells in February which may be critical for maize if this coincides with its flowering stage. As is the case for most other crops, maize is highly sensitive to water stress. It does not adjust as well as cotton, sorghum or wheat to water stress. There is slow leaf expansive growth, reduction of stomatal conductance and photosynthesis, and acceleration of leaf (hence canopy) senescence, when under water stress. Significant reduction of yield has been reported when maize suffers water stress in critical stages especially in flowering period because of its characteristics (MoAFS, 2012; Steduto et al., 2012). It is characterised as medium sensitive to salinity with similar responses to water stress. One of the major reasons for low world average yield is nitrogen deficiency. The most common deficiency is nitrogen, although potassium or phosphorus deficiency can be equally or more important in some soils (Steduto et al., 2012). In the field the effects of water stress are often confounded by nitrogen deficiency. The reason is that fertilizer nitrogen is applied to the top layer of the soil, which dries up first when water stress develops and essentially nitrogen becomes unavailable.

In Malawi maize production areas are classified according to altitude (MoAFS, 2012). These are low, medium and high altitude areas. Low altitude maize growing areas are less than 600 masl and are characterised by high summer temperatures (≥30°C) with a short rainy season (3-4 months) with annual total rainfall average between 700 to 800 mm. These areas are also called marginal maize growing areas associated with erratic rains and frequent droughts. An example of such an area is Kasinthula. The recommended cultivars best suited for these areas are early maturing cultivars. Medium altitude areas have altitude range from 600 to 1300 masl. These are characterised by moderate temperatures and fairly long rainy season of between 4 to 5 months. They receive an average annual rainfall of about 875 mm. Lilongwe is an example of such an area. High altitude maize growing areas are characterised by cool temperatures with altitudes above 1300 masl. In these areas maize takes long to mature because of low temperatures and they usually receive high rainfall for a longer period. Nyika plateau is an example for such areas.

Some recommended hybrid maize cultivars and their characteristics for different maize growing areas by the ministry of agriculture in Malawi are presented in Table 2-3. Take note that the information in the table was an extraction, and the presented cultivars are relevant for this research.

Table 2-3: Some recommended hybrid maize cultivars and their characteristics (Source: MoAFS, 2012)

Area	**Suitable maize cultivar**	**Days to maturity**	**Potential yield (t ha^{-1})**
Low altitude	SC 513	90-130	6
Low to medium altitude	SC 403	100-120	5-6
Medium altitude	SC 627	130-140	8-10
High altitude	SC 727	140-160	15

2.5.2 Sorghum

Sorghum is a crop indigenous to Africa and comes second after maize in terms of production. It is well adapted to tropical climates with several traits making it a drought-tolerant crop that survives under adverse climatic conditions, and thus is often relegated to poor soils and low-input management (Steduto et al., 2012). It is extensively grown under rainfed conditions for grain. In Malawi, sorghum is an important staple food in the Shire Valley and a food security crop in other marginal rainfall areas. Its characteristics makes it more adaptable to these areas. In Malawi, just like maize, sorghum is planted at the start of the rainy season and usually harvested in April depending on the cultivar. The growing cycle of early maturing sorghum cultivars, which include most hybrids, is 100 days or even less, whereas long season sorghum may last over 140 days. High production is achieved when sufficient water and nutrients are applied especially at critical stages of crop growth. But the average yields for sorghum smallholder farmers in Malawi are usually low around 0.7 t ha^{-1} (Table 2-2). This is because it is often grown in marginal areas under traditional low input practices based on landraces (Steduto et al., 2012). As a C4 crop, sorghum does not tolerate cool temperature regimes, hence its restriction to low and medium altitudes in Malawi. It is more tolerant to water stress in comparison to maize. If water stress occurs during flowering, sorghum produces tillers from nodes high on the stem to form branch heads to produce grain and compensate for at least part of the loss, provided that harvest can be delayed (Steduto et al., 2012). Excess water during the vegetative period results into high biomass with a low harvest index. This is due to excessive tillers which develop due to ample moisture among many cultivars. With the climatic conditions of Malawi, sorghum does not experience low temperatures, hence there is no reported effect of the same.

There are several cultivars of sorghum in Malawi, but majority of the farmers still cultivate local landraces. Most of the cultivars are recommended for low altitude areas but can do well in medium altitude areas. The hybrid cultivars and open pollinated cultivars can do well beyond estimated potential yields if well managed. Some examples of sorghum cultivars are presented in Table 2-4.

Table 2-4: Some recommended sorghum cultivars and their characteristics (Source; MoAFS, 2012)

Area	Suitable sorghum cultivar	Days to maturity	Potential yield (t ha^{-1})
Low to medium altitude	PN 3	90	3
Low to medium altitude	Pilira 1 (SPV 351)[a]	100-115	3.4
Low altitude	Pilira 2 (SPV 475)[a]	110-120	3
Low altitude	Gwiramtima	100-105	2.4-3.5

[a] = Open pollinated cultivar

2.6 Conclusion

The biophysical setting of the area and the crops which are relevant for this research have been presented in this chapter. The area is suitable for the production of the targeted crops for this research, maize and sorghum. It has been noted that the potential yields of these crops are higher than what the local farmers obtain. This information will be used in the next chapters.

Chapter 3
Social-economic status of farmers in the study area

3.1 Introduction

This chapter gives an overview of the socio-economic characteristics of the smallholder farmers in Malawi, compiled through a field survey of selected sample households in Lilongwe Agricultural Development Divisions (ADD) and Shire Valley ADD. These ADDs were selected as pilot areas with different climates and agronomical management practices. Knowledge of socio-economic status of the smallholder farmers of these two areas will help to properly characterise the regions of the study area, especially of the farmers' agronomical management practices. This was necessary when designing field experiments which incorporated local farming management practices. The information about the socio-economic status of these smallholder farmers played a key role in formulating solutions which are sustainable to their agricultural problems.

3.2 Materials and methods

3.2.1 Study sites

The study was carried out in Mitundu Extension Planning Area (EPA) in Lilongwe ADD and Mitole EPA in Shire Valley ADD. These EPAs are the closest to the experimental sites of this study.

3.2.2 Data collection methods and analysis

Thirty smallholder farmer households were interviewed using a questionnaire (Annex I) in each district. In-depth interviews were conducted with household heads using a structured questionnaire with both open and close ended questions. The questionnaire covered general socio-economic indicators, crop, soil and water management practiced by the farmers in the study area. It also covered information channels that these smallholder farmers use to get advice from extension staff or from knowledge passed on from one generation to another. One section focussed on the farmers' knowledge and experience on the changes in climate and the effects on their livelihood including their farming practices. In addition to the quantitative household survey, key stakeholders which included, agricultural extension development coordinators (AEDC), and agricultural extension development officers (AEDO) (who also advised in the selection of case study villages) were interviewed. The questions developed for these key stakeholder interviews were designed as guiding questions as discussions were expanded to other topics where possible. The survey followed a random selection approach in which enumerators conducted interviews, starting from the central location of a village and interviewing every third house in any direction. The exercise was conducted in August and September 2011 during the off-farming season. Descriptive statistics was used in analysing quantitative information collected during in-depth interviews from the structured questionnaires. The data was analysed statistically using SPSS 22.0 (IBM, 2013).

3.3 Results and discussion

3.3.1 Household characterisation

The living conditions in the rural areas reflect and influence the households' socio-economic characteristics and its behaviour. Usually in the rural setting of Malawi, the household head is responsible for the co-ordination of the household activities. In this study, the household head is defined as the person who makes decisions in the household (NSO, 2012). Furthermore, the National Statistical Office (NSO) of Malawi, defines a household as a person or group of persons related or unrelated who live together and make common arrangements for food or who pool their income for the purpose of purchasing food (NSO, 2008). As such inclusion of gender of household head and respondent can help to understand the structure of the smallholder households. From the survey, it was found that the majority of the households are male-headed in both districts, as illustrated in Table 3-1. The results are in line with the findings of the NSO integrated household survey of 2012 (NSO, 2012), which reports that more than 75% of households in the country are headed by males. This gives an indication that the farming practices in these areas are dependent on the preference of the head of the families in both these areas (in this case, men). This can be linked to the traditions of the local area, where a husband is regarded as a leader of the family. In their absence, wives are left to take many decisions about household matters as *de facto* (functional) heads. This usually happens as in most of the communities in Malawi, men tend to go to urban centres to seek extra work. This finding agrees with the findings of the NSO integrated household survey of 2012 (NSO, 2012).

Table 3-1: Household characteristics of the study area

Variable	**Location (ADD)**		
	Lilongwe (n=30)	**Shire Valley (n=30)**	**Total (n=60)**
Gender of household head (% of farm households)			
Male	90	93	92
Female	10	7	8
Education level of household head (% of farm households)			
None	10	40	25
Junior primary (up to 4 years)	20	20	20
Senior primary (from 5 to 8 years)	47	23	35
Secondary and beyond	23	17	20
Age group of household head (% of farm households)			
Below 20	0	0	0
20-30	10	10	10
30-55	73	77	75
Above 55	17	13	15
Average farm size (ha)	1.90 ± 1.33	1.86 ± 0.92	1.88 ± 1.14
Average household size (persons)	6 ± 1	5 ± 3	5 ± 2
Source of farm labour (% of farm households)			
Family	93	100	99
External (hiring) during peak period	73	8	50
Source of income (% of farm households)			
Farming	100	100	100
Small-scale business	67	0	34
Formal employment	3	27	15
Casual labour	13	17	15

The values for farm and household size are mean ± standard deviation

In both Lilongwe and Shire Valley, the typical household size was slightly higher than the national average of 4.6 persons per household (NSO, 2012) (Table 3-1). This scenario is common to many rural households, where a household usually consists of two adults and not less than 3 children (NSO, 2012), who usually provide farm labour plus other house chores. Almost all the respondents in both locations rely on family labour for their farming activities. About 50% of the respondents hire temporally labour only at peak times. Hiring people is more common in Lilongwe than in Shire Valley (Table 3-1). This is comparable with Wiyo (1999), who reported higher percentages of labour hiring at peak times (weeding and fertilizer application) in the central region. Other households consisted of extended families (grandparents, in-laws and other relatives). These households have an advantage to others in terms of labour input but are disadvantaged with regard to food security during off-season if the harvest was not good in the previous year (Alwang and Siegel, 1999).

A crucial factor to consider when assessing the socio-economic characteristics of a household is the age of the household head. It determines whether the household benefits from the experience of an older person, or has to base its decisions on the risk taking attitude of a younger household head (Snapp et al., 2002). In both sites, the majority of the household's heads belongs to the economically active group of 30-55 years. Few households have members that are over 55 years. This agrees with the results from integrated household survey of 2012 (NSO, 2012), which indicates that the most active population for agricultural purposes in Malawi is in the age bracket of 30 to 55 years. This implies that most of the smallholder farmers in these areas do their farming with the decisions based on risk taking to gain economic returns. Being the economically active group, the farmers are able to mix different enterprises to shield from the effects of harsh climate in the two sites.

While age is a crucial factor, the education level of the household head is another important attribute. For successful farming especially in the uptake of new innovations in farming as they are normally the decision makers. Education is a building block for human, political and socio-economic development, particularly important for poverty reductions because it empowers the poor, the weak and the voiceless by providing them with better opportunities to participate in national development (NSO, 2012). The education level of the household heads in the two sites was low as majority of the respondents did not go beyond secondary (Table 3-1). Comparing the two sites, Shire Valley was more illiterate than Lilongwe that has almost half of the household heads having gone to a senior primary level. These results compare well with the national estimates, that from the same age and occupational group, Shire Valley has lower literacy rates (47%) compared to Lilongwe (88%) of (NSO, 2012). Few household heads have gone to secondary school level and beyond in the two sites. Nevertheless, the general level of education in the two sites enables the farmers to do basic communications and monetary transactions which are crucial for their livelihoods. Another important advantage of the farmers who have some education is that they are usually selected as leaders by the government extension staff when they want to demonstrate new farming technologies (Alwang and Siegel, 1999; Chirwa, 2005; Place and Otsuka, 2001). The households who achieved a tertiary level of education are more able to interpret information than those who have less or no education.

3.3.2 Sources of income

Generally, rural households in Malawi are poor, and their main source of income is from selling some produce from their farm produce (Table 3-1). The non-agricultural related activities also contribute as sources of monetary income. Farmers in Lilongwe tend to be involved in small-scale business. In Shire Valley extra income is generated from provision of casual labour services and employment. This is because farmers in Shire Valley are closer to sugar plantations where they easily get employment in the sugarcane fields. The farmers in Lilongwe live close to the city of Lilongwe, where starting a small-scale business is easy as there are already readily available consumers. The farmers in both locations reported that they only sell surplus farm products when they need services which require them to pay in monetary terms.

3.3.3 Farm sizes

Insufficient and small land holding sizes for agricultural production constitutes one of the most constraining resources facing rural households in Malawi (Alwang and Siegel, 1999). In this study, the average farm sizes for the smallholder farmers is 1.8 hectares (Table 3-1). These results are in agreement with results from Wiyo (1999), who found that the smallholder farmers in Malawi usually have small plots of less than 1 hectare on average. This obviously creates a problem for introducing farm mechanisation to the smallholder farmers as there is a lot of fragmented farm plots that cannot be transformed into one large field. Because of the small farm sizes, farmers supplement their harvest by cultivating wetlands or riverbanks (locally known as "*dimba*").

They take advantage of the residual moisture after the rainy season through small scale irrigation plots. It is also reported that smallholder farmers in Malawi supplement their harvest with wetland farming (Tchale, 2009; Veldman, 2012; Wiyo, 1999). Irrigation is applied using small buckets and watering canes and water drawn from hand dug wells. Crops cultivated are mostly vegetables and maize that is harvested green, which are grown on raised beds around hand dug wells. This is common in Lilongwe where over 50% of the respondents reported that they possess a dimba compared to Shire Valley where very only 3% of the respondents have a dimba. This is because the respondent in Shire Valley were situated away from river banks and wetlands although very few households (3%) reported that they have a vegetable garden around their homes.

3.3.4 Common crops grown

The most commonly grown crop by the farmers in the two sites is maize. This was expected as in Malawi, maize is a staple food (Table 3-2). This agrees with Wiyo (1999) who reported farmers first main crop is a food crop in this case maize. Other crops include groundnuts, cotton, sorghum and soy beans. The climate of the two areas influences the type of crops suitable for cultivation. For example, apart from maize, most farmers (>70%) grow sorghum and cotton in Shire Valley. Lilongwe farmers give preference to the cultivation of groundnuts and soya. The climatic conditions favour cultivation of sorghum and cotton in Shire Valley, as it receives little rain and has high temperatures (Section 2.3).

Table 3-2: Common crops and preferred hybrid cultivars in the study area

Variable	**Location (ADD)**		
	Lilongwe (n=30)	**Shire Valley (n=30)**	**Total (n=60)**
Crop grown (% of farm households)			
Maize	100	100	100
Groundnuts	100	0	50
Cotton	0	87	44
Sorghum	0	70	35
Soy beans	67	0	34
Preferred hybrid cultivar (% of farm households)			
DK 8033[a]	57	3	30
SC 403[a]	3	47	25
Pilira[b]	0	100	50

[a]: maize cultivar; [b]: sorghum cultivar

Hybrid cultivars are the most planted crops in the two areas. They are preferred by farmers due to the unexpected and unpredictable climate in the recent times in the two areas. Local cultivars are used less frequently because they are less resistant to recent harsh conditions of climate. A combination of hybrid and local seeds also occurs often. The common cultivars grown are the early maturing cultivars for both maize and sorghum. The use of cultivars that have shorter growing period, can be beneficial in regions were the rainy season seems to shorten as a result of climatic variability and change.

For maize, the most common types are DK8033 usually grown in Lilongwe and SC403 most popular in Shire Valley (Table 3-2). SC403 is a drought resistant and short maturing maize cultivar produced by SEED-CO Malawi. The crop has a growing cycle of 90-110 days. Furthermore, its potential yield is 3-6 t ha^{-1} (SeedCo, 2009). DK8033 is a high yielding maize cultivar with a longer growing cycle of 115-130 days (MoAFS, 2012). The potential yield can reach 8-9 t ha^{-1} which is more than SC403. Pilira is an open pollinated cultivar of sorghum that was made using conventional breeding (Nkongolo et al., 2008). Very few farmers still grow local cultivars of sorghum, but Pilira is favoured because of its early maturity and drought tolerance as most important characteristics (Nkongolo et al., 2008). Most respondents who cultivate sorghum are from Shire Valley. In Lilongwe, farmers are not familiar with sorghum in their diets. This infers that farmers concentrate on producing food which is profitable and aligned to their diets.

3.3.5 Crop management practices

The most reported cropping pattern in the two areas, is that most farmers plant maize or sorghum alone (Table 3-3). Nonetheless, farmers practice intercropping with groundnuts and the pulses. This was more frequently observed in Lilongwe than in Shire Valley. This observation goes in line with findings by Wiyo (1999), who reported that most of the farmers in central Malawi practice intercropping since the drought of 1992. Farmers in Shire Valley reported lack of inputs and harsh climatic conditions for their failure to implement intercropping. However, they acknowledged the importance of intercropping. This is reflected in the response on the knowledge of field management practices. All the respondent acknowledged the importance of different crop and field management practices. This might be the effect of following guidelines by extension staff who encourage farmers to be risk-averse and avoid strict mono-cropping especially in times of adverse weather effects. Farmers hardly change their cropping patterns although acknowledging their importance. This concurs with Wiyo et al. (1999), who reported that farmers do not change their cropping patterns as a response to climatic conditions but rather stick to familiar crops they know its management very well. Main factors influencing these cropping patterns include household food security and income sources, advice of extension workers, past rainfall patterns and the need to use every available space in their small plots (Table 3-3).

Table 3-3: Cropping patterns and management practices

Variable	**Location (ADD)**		
	Lilongwe (n=30)	**Shire Valley (n=30)**	**Total (n=60)**
Cropping pattern (% of farm households)			
Maize alone	100	60	80
Maize and groundnuts	100	0	50
Maize and common pulses	0	87	44
Sorghum alone	0	100	50
Factors influencing cropping patterns (% of farm households)			
Household food security	67	70	69
Income source	30	67	49
Extension advice	67	67	67
Past rainfall patterns	23	33	28
Use of available space	33	17	25
Soil and water management techniques (% of farm households)			
Box ridges	67	53	60
Mulching	33	70	52
Main farming problems (% of farm households)			
Lack of inputs	67	70	69
Poverty (lack of money)	60	70	65
Poor rainfall	33	80	57
Pest and diseases	47	50	49
Lack of markets	0	93	47

Enhancing the productivity of the soil is usually done through boosting its fertility level. In this study, the farmers were asked if they use fertilizer in their management practices. All respondents use a form of fertilizer: organic (manure), inorganic or a combination of both. The mentioned types of inorganic fertilizer that farmers use are 23:21:0+4S (N:P:K) and UREA for basal and top dressing respectively. Organic fertilizers are compost and animal manure. Farmers were not able to give the quantities used as they just apply as efficiently as possible to cover the whole plot without following the guidelines. The respondents reported that they usually have difficulties in getting inorganic fertilizers as these are expensive and their supplies are sometimes erratic in the area. The problems farmers usually face in their farming include; lack of inputs, shortage of money, poor rainfall/water shortage, pests and diseases on the crops, and marketing (Table 3-3). A lot of farmers reported lack of markets as their main problems in Shire Valley because of their location as access to the markets is poor and low production unlike in Lilongwe. Lilongwe farmers are close to the capital where markets and access to them are readily available. Lack of inputs and poverty were highly ranked in both areas while Shire Valley added poor rainfall as one of the major problems. These problems have been reported in several studies (Alwang and Siegel, 1999; Chirwa, 2005; Orr and Ritchie, 2004; Snapp et al., 2002; Wiyo, 1999) reporting about smallholder farmers in Malawi. The farmers in the two sites practice soil and water conservation techniques in their fields to control soil erosion and harvest water to keep the soil moist especially during dry spells. The most used methods include box ridges and mulching (Table 3-3).

3.3.6 Perception towards climate change

One of the objectives of this research was to understand how smallholder farmers view and make decisions concerning their farming activities and how they adapt to climate change. The farmers were asked what they experienced as a change between current times and three decades ago. All respondents indicate that climate is changing. Interestingly farmers pointed out that they experience a change in rainfall amount and distribution. Recently, rains have become unreliable both in timing and amount of dry spells. The rainy season seems to begin later and end sooner which results in a shorter growing season. Respondents claim that the start of the rainy season is no longer October, but rather November and even sometimes December. The respondents also reported that the frequency of dry spells within the season has increased without quantifying. These results compare well with a recent research by Simelton et al. (2013) and in Chapter 4 of this thesis, where these claims were proved with observed data. Although these changes are noticed by every smallholder farmer, not all of them experience this as a bad evolution. Thirteen out of 60 farmers think the climate change has a positive influence on their harvest. The respondents reported that they switched to start growing hybrid cultivars of maize or sorghum that are designed to be drought-resistant. Farmers who believe that climate change has a negative impact on their harvest, employ several adaptive management techniques as presented in Table 3-4.

Table 3-4: Farm management techniques to mitigate effect of climate and information sources

Variable	**Location (ADD)**		
	Lilongwe (n=30)	**Shire Valley (n=30)**	**Total (n=60)**
Adaptive management techniques (% of farm households)			
Planting early maturing cultivars	67	70	69
Use of organic fertilizers	30	67	49
Box ridges	67	67	67
Early planting	23	33	28
Conservation agriculture	33	17	25
Increasing inorganic fertilizer rates	23	17	20
Information source (% of farm households)			
Extension service	100	83	92
Radio	67	67	67

3.3.7 Information sharing networks

Sharing and access to information is very important in farming as it provides an environment for learning and helping out those who struggle in their fields. In the modern world, information can be accessed through numerous ways. The respondents get most of the important farming information from government extension service personnel. Radios were also reported to be very useful source of important agricultural related information. Examples of information shared include; planting guidelines, planting dates, cultivars, management practices, markets and farm business.

3.4 Summary and conclusion

In summary, the socio-economic status of Malawian smallholder farmers has been presented in this chapter based on a pilot survey of 60 farmer households in two areas. Evidence presented suggests generally that the smallholder farmers are still poor and face a lot of limitations in their farming practices but they still strive to improve their livelihoods despite the myriad constraints they face. These constraints combined with their economic status makes their farming practices stagnant and not improving the harvest year to year. The small and defragmented farming plots make the introduction of large mechanisation like tractors, which may ease some farm operations, complicated. However some form of mechanisation are still applicable although not usually practiced at these small farms. These include animal traction ploughs, herbicide spraying (sorghum and cotton), jab-planters in no-till or minimum tillage systems, are usually used. Even though they have their own ways of survival they still lack a clear direction in terms of facing and adapting to the reality and effects of climate change. The farmers value the importance of extension workers in their fields and rely often on information concerning their farming given by these extension workers and via radios.

A closer look into the descriptive statistics comparing the two sites reveals that most of the households are male headed with activities and labour shared among family members. The households have small sized plots for their household food security. The household heads are educated up to senior primary school level in Lilongwe whereas in Shire Valley most of the farmers have no basic education. This might affect the uptake and implementation of new technologies in farming. The 30 to 55 years age group is mostly the economically active group which usually make risk decisions in their farming practices as long as they make sure their livelihoods improve or they survive. Farming information is usually passed on from generation to generation as the children provide labour to the households' in turn learning faring techniques from parents. Once, they become household heads, they add this information with advices from extension services and radios for their agricultural production.

Regarding the income sources, the main source of income is selling surplus agricultural products for Lilongwe and being engaged in temporary employment in Shire Valley. The farmers tend to favour staple foods for their survival rather than cash crops as they focus mainly on subsistence farming. The main constraint is the fertility status of the soils which are usually cultivated every year with little or no nutrient replenishment. Even though most of the farmers from the two sites use inorganic fertilizers, the quantities applied are usually too small to have a pronounced effect on their yields. This is due to lack of economic muscle to purchase the expensive fertilizers and also heavy reliance on subsidised farm inputs from the government. The crops grown are mainly maize in Lilongwe and sorghum in Shire Valley.

The farmers realise that the climate is changing and they follow up keenly the advice from extension services as well as messages from meteorological department through the radio despite ambiguities and confusion which are usually associated with such methods. Nevertheless, farmers are willing to learn and adapt to the effects of climate change, so that their livelihoods can improve.

Chapter 4
Effect of rainfall variability on the length of the crop growing period over the past three decades[a]

4.1 Introduction

Rainfed agriculture is highly sensitive to water availability. Assessing trends of rainfall characteristics based on past records is essential for developing suitable farming strategies (Hadgu et al., 2013) in different areas. Because of the marked seasonal nature of rainfall, crop selection and planning of farm activities for a successful season are difficult, and production is vulnerable (Raes et al., 2004). Therefore presence of a relationship between onset, cessation dates and LGP is relevant for planning agronomic activities in the season (Mugalavai et al., 2008). Thus the aim of this study was to investigate the characteristics and trends of rainfall in central Malawi, the main region for maize production in the country. The focus of the study was on the onset, cessation and LGP, which are crucial for effective rainfed crop production. The study only focussed on central region of Malawi which has three Agricultural Development Divisions (ADDs), Lilongwe, Kasungu and Salima, due to data limitations in the other regions. Maize was selected as it is largely produced in the central region, mostly by smallholder farmers.

4.2 Materials and methods

4.2.1 Study site

The study was conducted in the central region of Malawi, between latitudes 12.5° and 14.5° S and longitudes 33° and 34.7° E (Figure. 1), where 90% of the economic activities are agro-based.

[a] Adapted from: Fiwa, L., Vanuytrecht, E., Wiyo, K.A., Raes, D. 2014. Effect of rainfall variability on the length of the crop growing period over the past three decades in Central Malawi. *Clim Res* (62): 45 – 58.

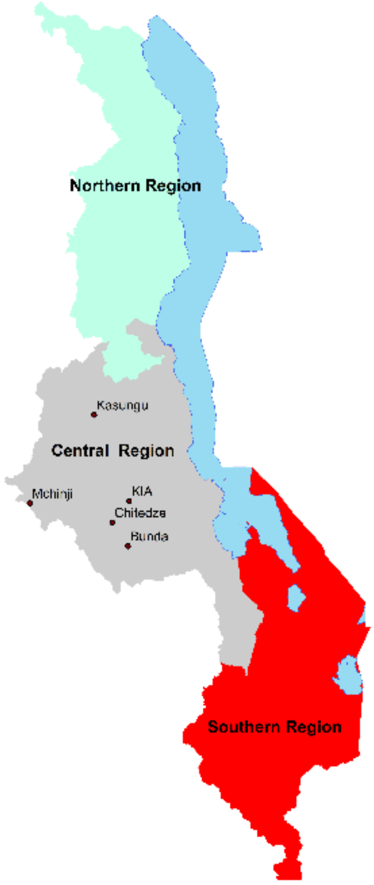

Figure 4-1: Regional map of Malawi, showing location of meteorological stations used in this study (Source: Malawi Land Resources Conservation Department)

The area has a favourable climate for crop production. Its average temperature is from 16 to 26°C, with annual average rainfall between 900 and 1200 mm, mainly concentrated in the period from November to April. The monthly reference evapotranspiration (ET_o) ranges from 90 mm in winter (May, June and July) to a peak of 180 mm in October (Figure 4-2).

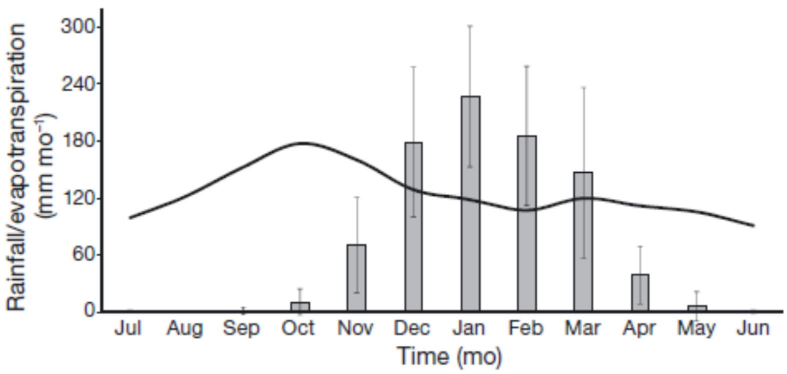

Figure 4-2: Average (1970-2012) monthly rainfall (bars; error bars: standard deviation) and reference evapotranspiration (bold line) of the central region of Malawi (Source: Malawi Department of Climate Change and Meteorological Services)

The area has predominantly red soils (ferric Luvisols) (Wiyo et al., 1999) with a sandy clay loam texture (Saka et al., 2003). These soils are generally well structured, deep and well drained. Ferric Luvisols are highly productive; hence, the central region produces most of the maize in Malawi.

4.2.2 Meteorological data

Long series of daily rainfall from five meteorological stations in the central region of Malawi were collected from the Malawi Department of Climate Change and Meteorological Services (Table 4-1). Additional climatic data (minimum and maximum temperature, relative air humidity, solar radiation and wind speed) for computing reference evapotranspiration (ET_o) with the FAO-Penman Monteith equation (Allen et al., 1998) were obtained from the FAO New_LocClim climate estimator (FAO, 2005).

Table 4-1: Geographical description of meteorological stations used in the study (30 year period, 1980-2009).

Station	Latitude (° S)	Longitude (° E)	Altitude (masl)
Bunda	14.18	33.77	1118
Chitedze	13.97	33.63	1149
Kasungu	13.02	33.47	1058
KIA	13.78	33.78	1229
Mchinji	13.80	32.90	1181

KIA: Kamuzu International Airport; masl: meters above sea level

4.2.3 Onset, cessation and length of growing period (LGP)

The onset of the rainy season was determined for each station as the first day of the first 10 day-period of the rainy season with a total rainfall of 25 mm, on the condition that it is followed by two 10 day-periods with at least 20 mm of cumulative rainfall (AGRHYMET, 1996; Hachigonta et al., 2008; Harrison et al., 2011). With these conditions, the initial moisture requirements for seed germination and crop establishment are considered. It also ensures that the soil moisture levels are high enough in the topsoil to sustain initial crop development. This criterion is adopted from the Famine Early Warning System, which was developed at the Agriculture-Hydrology-Meteorology (AGRHYMET) Regional Center in Niger. To avoid false starts of the rainy season, the search period was set from 1 October.

The cessation date of the rainy season was determined for each station based on the method used by Mhizha et al. (2012). It tailors cessation to crop and soil type by considering the ratio of actual evapotranspiration (ET_a) to ET_o, against the crop coefficient (K_c) at maturity. The cessation date was picked as the first day after 15 February when the ratio of ET_a to ET_o dropped below 0.35, which is the K_c value of maize at maturity (Allen et al., 1998). The initial search day of 15 February was selected to exclude and minimise the influence of mid-season dry periods (Mhizha et al., 2012), which usually occur in this area especially during the rainy season (Nyakudya and Stroosnijder, 2011; Usman and Reason, 2004). Another assumption is that the crop will have by this time surpassed the critical stage in its early development. In contrast to methods based on rainfall only (Hadgu et al., 2013; Mupangwa et al., 2011; Tadross et al., 2009) this method considers cessation of the growing period as a function of crop characteristics, soil water conditions and soil type in addition to the evaporating power of the atmosphere and rainfall of the location (Mhizha et al., 2012).

The soil water balance model BUDGET (Raes et al., 2006a) was used to simulate ET_a on a daily time step. ET_a dropped below crop evapotranspiration ($ET_c = K_c \times ET_o$) when 55% of total available water was depleted. The crop was allowed to transpire beyond the normal crop cycle length as long as the available soil water allowed it. This was done by extending the normal period and keeping constant the crop characteristics ($K_{c,mid}$) of the mid-season stage (the mid-season until the end of the season was extended from 75 d to 200 d). The daily ratio of ET_a to ET_o was observed. The date when the ratio was below 0.35 was selected as the cessation date. Table 4-2 shows the maize crop characteristics that were taken from Doorenbos and Kassam (1979) and Allen et al. (1998).

Table 4-2: Crop parameters for maize. Source: Doorenbos and Kassam (1979); Allen et al., (1998)

Growth stage	**Length of growth stages (d)**	**Rooting depth (m)**	**K_c (crop coefficient)**
Initial	20	0.3	0.17 (dry), 1.1 (wet top soil)
Crop development	40	0.3 – 1.2	(0.17 - 1.1) to 1.17
Mid-season until the end of season	75	1.2	1.17 to 0.35

The soil type used in all the simulations was sandy clay loam, which is commonly found in the central region of Malawi (Saka et al., 2003). Characteristics of the soil used in the simulations (Table 4-3) were obtained by means of a pedotransfer function (Saxton et al., 1986; Saxton, 2003) based on soil texture analysis. The LGP was calculated for each station as the period between the onset and cessation date, expressed in calendar days.

Table 4-3: Soil characteristics of the study area used in the simulations.

Soil type	**PWP (vol%)**	**FC (vol%)**	**SAT (vol%)**	**TAW (mm m^{-1})**	**K_{sat} (mm d^{-1})**
Sandy clay loam	14.9	25.8	44.1	110	360

PWP: permanent wilting point; FC: field capacity; SAT: saturation point; TAW: total available water; K_{sat}; saturated hydraulic conductivity

4.2.4 Trend analysis

4.2.4.1 Test of randomness and persistence

Trend detection in time series requires data that are random and persistence-free (Ngongondo et al., 2011) to solve the confounding effect of serial dependence when interpreting the results. Kulkarni and Von Storch (1995) argue that if the data series contain positive correlations, the non-parametric test could indicate a significant trend due to random effects of the data series. Therefore, in our study, the rainfall time series for each station was tested for randomness and independence using an autocorrelation function as described by Von Storch (1995) as follows:

$$r_k = \frac{\sum_{i=1}^{N-k}(x_i - \bar{x})(x_{i+k} - \bar{x})}{\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad \textit{Equation 4-1}$$

Where r_k is the lag$-k$ autocorrelation coefficient, $\bar{x}$ is the mean value of a time series x_i, N is the number of observations, and k is the time lag. Random series have autocorrelations near zero for all time lag separations, except the zero lag coefficient which is always 1. In that case, statistical tests are directly applied to the series. Non-random series have ≥1 significantly non-zero autocorrelation values, and statistical tests in this case are applied to a pre-whitened series to account for the non-randomness.

4.2.4.2 Mann-Kendall test

There are numerous tests for detecting and estimating trends in meteorological data. The World Meteorological Organisation (WMO) recommends the non-parametric Mann-Kendall (MK) test statistic (Kendall, 1975; Mann, 1945) for the assessment of trends in meteorological data (WMO, 1988). The MK test is simple, robust and minimally sensitive to outliers and missing data (Ngongondo et al., 2011; Tabari et al., 2014). The test is also recommended for non-normally distributed data series such as rainfall (Lettenmaier et al., 1994). The MK test has been widely applied in various trend-detection studies (Batisani and Yarnal, 2010; Hadgu et al., 2013; Ngongondo et al., 2011; Tabari et al., 2014). In our study, the MK test was applied at a significance level of 5% to detect temporal trends in onset, cessation and LGP time series. The test statistic is computed as follows:

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if \quad S < 0 \end{cases} \qquad \textit{Equation 4-2}$$

in which

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\,(x_j - x_i) \qquad \textit{Equation 4-3}$$

The variance of *S*, for the situation where there may be ties (that is, equal values) in the *x* values, is given as follows:

$$Var(S) = \frac{1}{18}[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)\,(2t_i + 5)] \qquad \textit{Equation 4-4}$$

where the x_j and x_i are the sequential data values, m is the number of tied groups (a tied group is a set of sample data having the same value), t_i is the number of data points in the i^{th} group, n is the length of the data set, *S* is the MK test statistic, Z_{MK} is the normalized MK test statistic and $\text{sgn}(x_j - x_i)$ is equal to 1, 0, -1 if $(x_j - x_i)$ is greater than, equal to, or less than zero, respectively (Tabari et al., 2014). The presence of a statistically significant trend is evaluated using the Z_{MK} value. The positive (negative) values of Z_{MK} indicate increasing (decreasing) trends and the value $Z_{1-\alpha/2}$ denotes a quantile of the standard normal cumulative distribution. The null hypothesis H_0, should be accepted if; $-Z_{1-\alpha/2} \leq Z_{MK} \leq Z_{1-\alpha/2}$ at a given level of significance (where α is a chosen level of significance).

4.2.4.3 Cumulative sum test

To find out in which year (or years) an abrupt change occurred in the time series, the cumulative sum (Cumsum) technique (Tabari et al., 2014) was used to identify the change point. The 'Cumsum' is calculated as follows (Kiely, 1999):

$$S_k = \sum_{t=1}^{k}(x_t - \bar{x}), \ k = 1,2, \dots, n$$ *Equation 4-5*

where $\bar{x}$ is the average value of the time series. The possible change occurs when S_k is at maximum. The Cumsum test was applied to the time series with significant trends.

4.2.5 Variability evaluation

The coefficient of variation (CV) was calculated to evaluate the extent of variability of onset, cessation and LGP by dividing the standard deviation of the event by its mean. CV is calculated as follows;

$$CV = \frac{\sigma}{\mu} \times 100\%$$ *Equation 4-6*

Where;

CV is the coefficient of variation (%);
σ is the standard deviation and;
μ is the mean

4.2.6 Changes in rainfall amount and number of rainfall events

To assess the long-term changes of rainfall in terms of total amounts and number of rainfall events in the region, two 15 year periods were compared. The data were divided into 2 groups owing to the results from the Cumsum technique, which was applied to time series that showed statistically significant trends. Our assumption is that the behaviour of rainfall changed after the 1995/96 season (based on the Cumsum results). The data were divided into an earlier period (1980 to 1994) and a later period of 1995 to 2009. Simelton et al. (2013) also reported similar changes in rainfall for central Malawi from the 1996/97 season onward, which indicates the notion of abrupt changes as indicated by the Cumsum results. Both the total rainfall amount and the number of rainfall events were calculated for each month. The threshold used for defining a significant rainfall event was 5 mm. This value is suitable for regions experiencing pan evaporation of ~5 mm d^{-1} (Figure 4-2) and as an amount that can have significant influence on crop growth (Stern et al., 2003; Woltering, 2005).

4.3 Results

4.3.1 Serial correlation

The daily rainfall time series for each station did not reveal any significant serial correlations at all lags. The stations are not correlated to each other, as presented in Table 4-4. These time series were therefore random, meeting the independence distribution criteria. Therefore, the analysis of the trends of the rainfall characteristics did not require any further data manipulation, and the MK test was applied directly.

Table 4-4: Cross-correlation coefficients among the stations

	Bunda	Chitedze	KIA	Kasungu	Mchinji
Bunda	1	0.33	0.28	0.11	0.25
Chitedze		1	0.42	0.13	0.36
KIA			1	0.13	0.31
Kasungu				1	0.11
Mchinji					1

4.3.2 Onset of growing season

Figure 4-3 shows the time series of onset dates of different stations in central Malawi. There is year-to-year variation, with all stations showing a tendency of the onset date being delayed from the last 10 day period of November in the beginning of the time series to the second 10 day period of December toward the end of the time series. The mean onset date is similar in all stations but Chitedze (Table 4-5). The pattern displayed by Chitedze is more closely linked to early start of the rains than the rest of the stations that fulfil the criteria used to define the onset. These dates are characterized with high standard deviation (ranging from 13 to 22 days), which indicates that the onset date in the last 30 years has been changing significantly in most stations. The MK test revealed a statistically increasing trend at 95% level of confidence in all stations but KIA. The increasing trend means that the onset dates tends to start later in the season at all stations. There is high variability (CV ranging from 13 to 34%) in the onset dates (Table 4-5), which creates difficulties in decision making for crop management especially regarding planting dates in the region. The 1995/96 season marks the time when an abrupt change in the onset dates was observed for Bunda, Chitedze, Kasungu and KIA, whereas for Mchinji, this change occurred in the 1996/97 season.

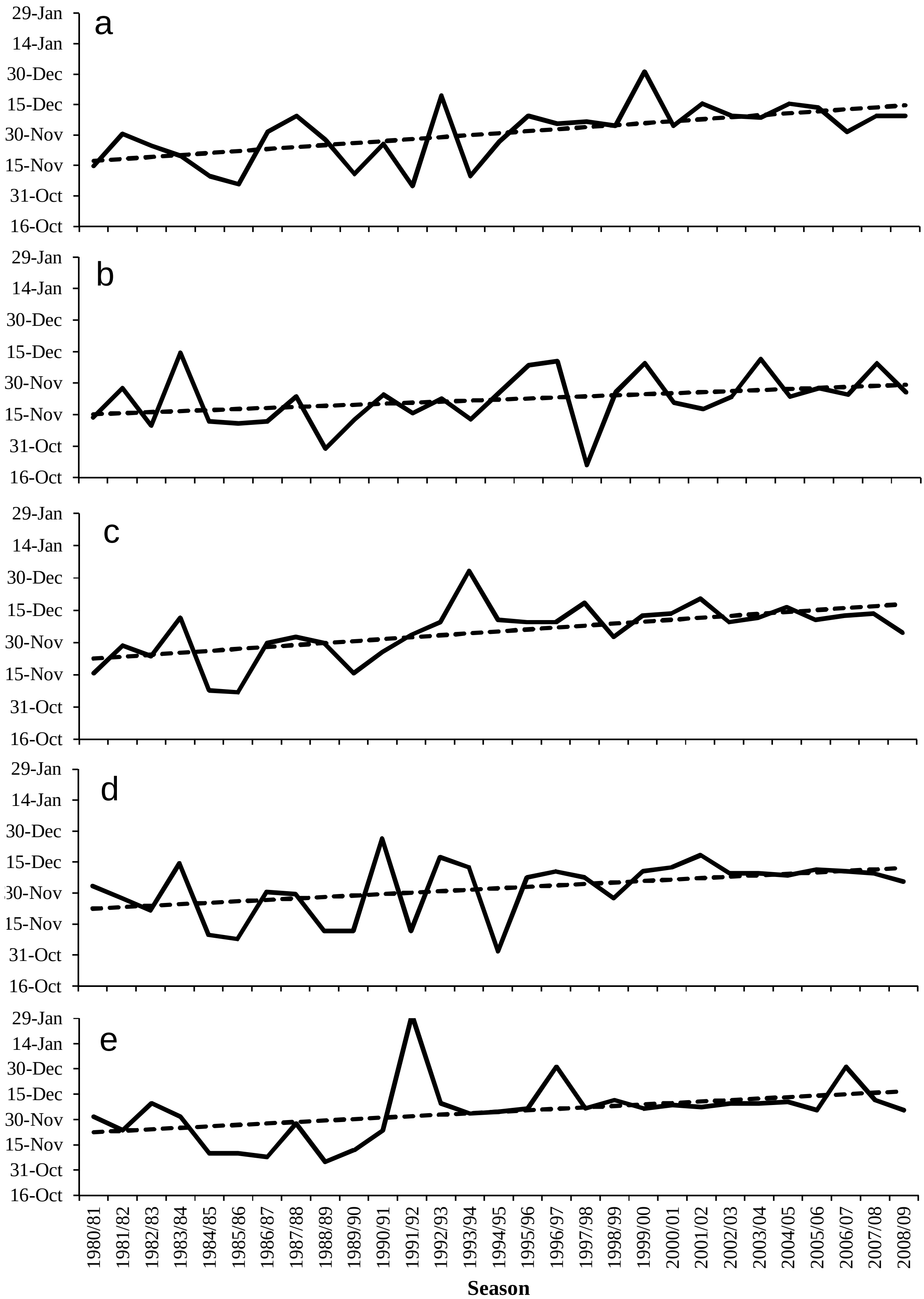

Figure 4-3: Time series of onset dates for the central region of Malawi from the seasons 1980/81 to 2008/09 (a: Bunda; b: Chitedze; c: Kasungu; d: KIA; e: Mchinji). The dotted line shows the linear trend of the data points

4.3.3 Cessation of growing season

Figure 4-4 shows the time series of cessation dates for different stations in central Malawi. Mean cessation dates in all the stations are similar (around the last 10 day period of April) with high standard deviations (ranging from 11 to 27 days) as presented in Table 4-5. There is on average an earlier cessation of 15 days between 1980/81 and 2008/09 in these stations, approximately 5 days per decade. The MK test indicates a general decreasing trend at 95% confidence level in the cessation dates for all the sites except Kasungu. Contrary to the standard deviation, coefficients of variation are generally low in all stations, indicating low variability and possibly relatively stable cessation dates in the region but still unpredictable. A stable cessation date is advantageous to farmers in planning for off-season farming activities. These activities include searching for markets, processing farm produce and winter farming.

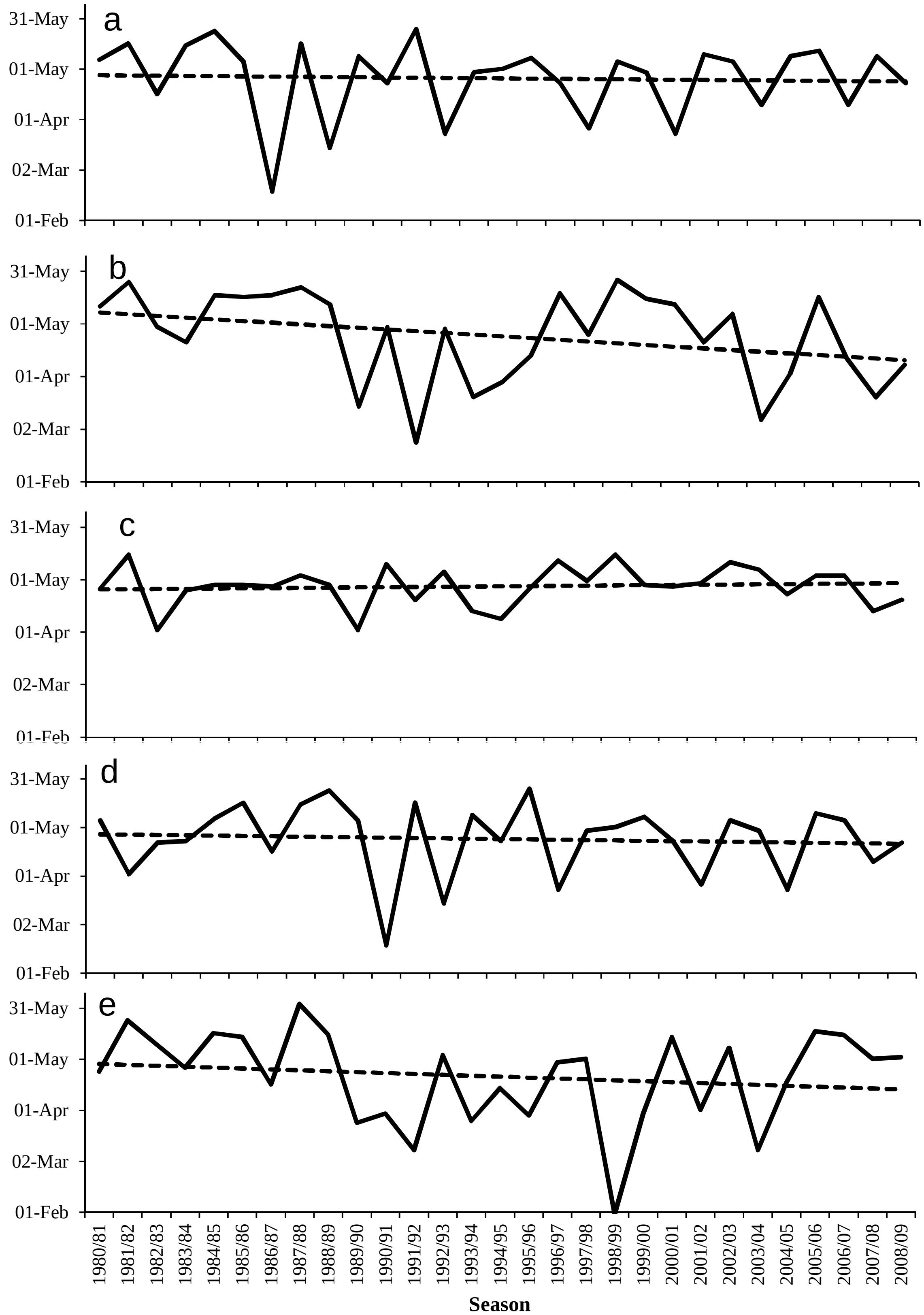

Figure 4-4: Time series of cessation dates for the central region of Malawi from the seasons 1980/81 to 2008/09 (a: Bunda; b: Chitedze; c: Kasungu; d: KIA; e: Mchinji). The dotted line shows the linear trend of the data points

4.3.4 Length of growing period (LGP)

Figure 4-5 shows the time series of the LGP for different stations in central Malawi. There is a general decreasing trend, following the general delay in onset and the advancement of the cessation date. The average LGP in the study region varied from 135 to 149 days depending on the location of the station (Table 4-5). Kasungu and KIA had 137 days, Mchinji had 135 days, while Bunda and Chitedze had 140 and 149 days respectively. However, all stations displayed high standard deviations (ranging from 16 to 36 days), which indicates how the LGP varies in time among the stations. The coefficient of variation in all stations but Kasungu (12%) showed high (ranging from 12 to 27%) year to year variability of LGP. This indicates how risky it is to rely on one type of crop in areas where LGP is constantly varying. Knowledge of the LGP is very useful in planning the type of cultivars to be grown based on their maturity period. All the stations revealed that the LGP has decreased in the last 3 decades. The MK test revealed a statistically significant decreasing trend in LGP at Chitedze and Kasungu. The 1995/96 season was when an abrupt change occurred.

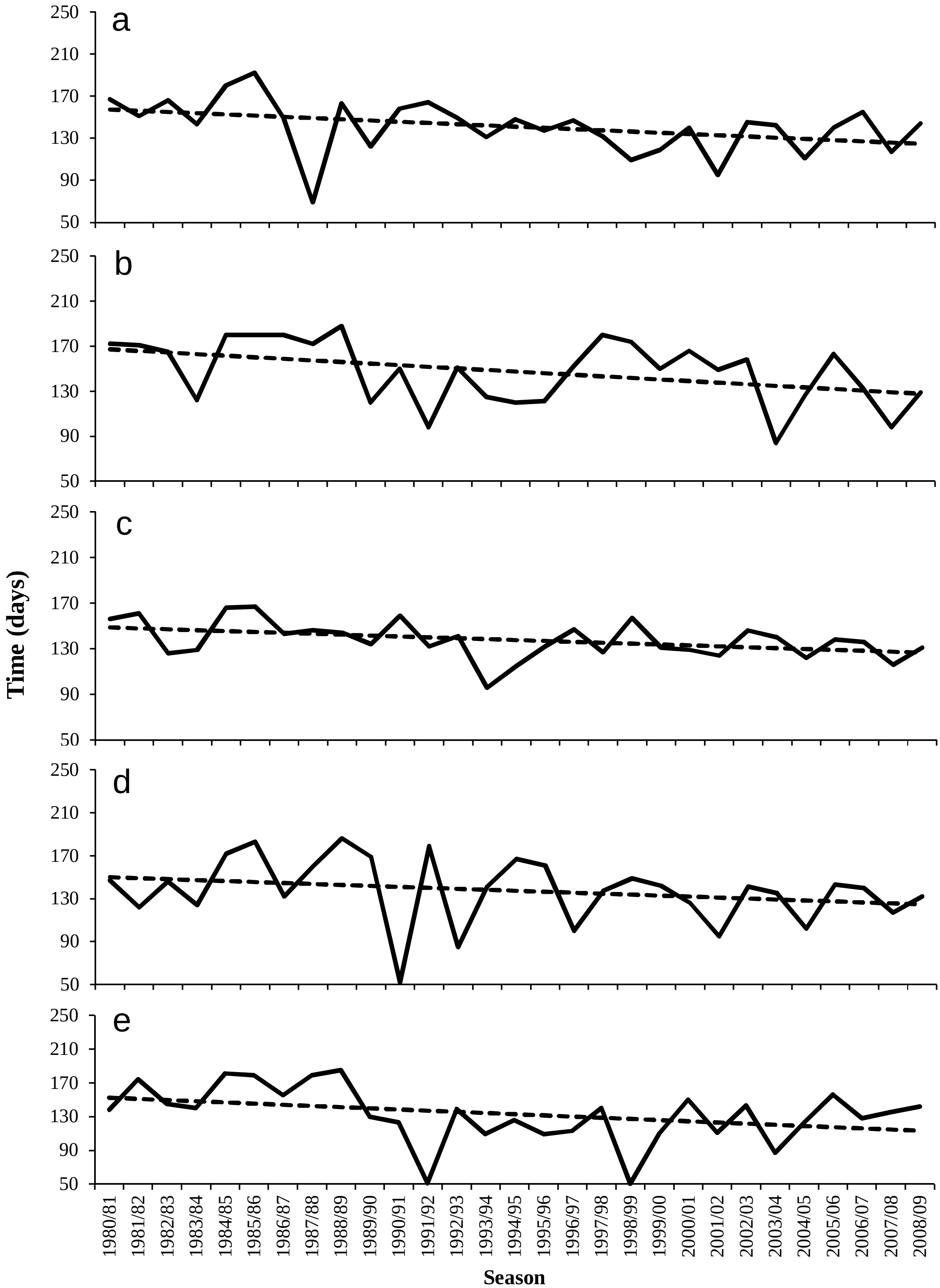

Figure 4-5: Time series of length of growing period for the central region of Malawi from the seasons 1980/81 to 2008/09 (a: Bunda; b: Chitedze; c: Kasungu; d: KIA; e: Mchinji). The dotted line shows the linear trend of the data points

Table 4-5: Statistical summary of onset, cessation dates and length of growing period (LGP) of central Malawi over the period of 1980 to 2009.

Statistic	**Station**				
	Bunda	**Chitedze**	**Kasungu**	**KIA**	**Mchinji**
Onset date					
Mean	2-Dec	22-Nov	6-Dec	3-Dec	2-Dec
SD (days)	14	13	13	14	22
Z_{MK}	3.11*	2.36*	3.71*	1.74	2.29*
CV(%)	21	22	13	34	19
Cumsum	1995/96	1995/96	1995/96	-	1995/96
Cessation date					
Mean	21-Apr	21-Apr	22-Apr	19-Apr	16-Apr
SD (days)	21	21	11	21	27
Z_{MK}	-0.51	-1.82	0.56	-0.49	-0.53
CV(%)	10	10	12	13	05
LGP (days)					
Mean	140	149	137	137	135
SD	28	28	16	31	36
Z_{MK}	-1.651	-2.05*	-2.27*	-1.63	-1.73
CV(%)	20	19	12	22	27
Cumsum	-	1995/96	1995/96	-	-

Z_{MK} is Mann-Kendall trend test; *is statistically significant trend (α=0.05); SD is standard deviation; CV is coefficient of variation; LGP is length of growing period; Cumsum is cumulative sum test showing the season where an abrupt change occurred in statistically significant trend results.

4.3.5 Changes in rainfall amount and number of rainfall events

Figures 4-6 and 4-7 show the number of rainfall events per month and the total monthly rainfall amount in the rainy season for the 2 periods, i.e. 1980-1994 and 1995-2009. The two periods are significantly different at 95% confidence level. The earlier period (1980 to 1994) has a longer rainy season with the rainfall events spread over the 6 months of the wet season for Bunda, Chitedze, Kasungu and KIA. However, in the later period (1995 to 2009), both the total seasonal rainfall and the number of rainfall events during the first and last months of the rainy season were lower, whilst there is a high peak of rainfall in January. More rain fell in the month of January in the later period (1995 to 2009). There was high variability in the rainfall amounts in all the stations as indicated by the large error bars in the graphs (Figure 4-7). Mchinji station had a decline in both the monthly rainfall amounts and the number of rainfall events in a month during the rainy season.

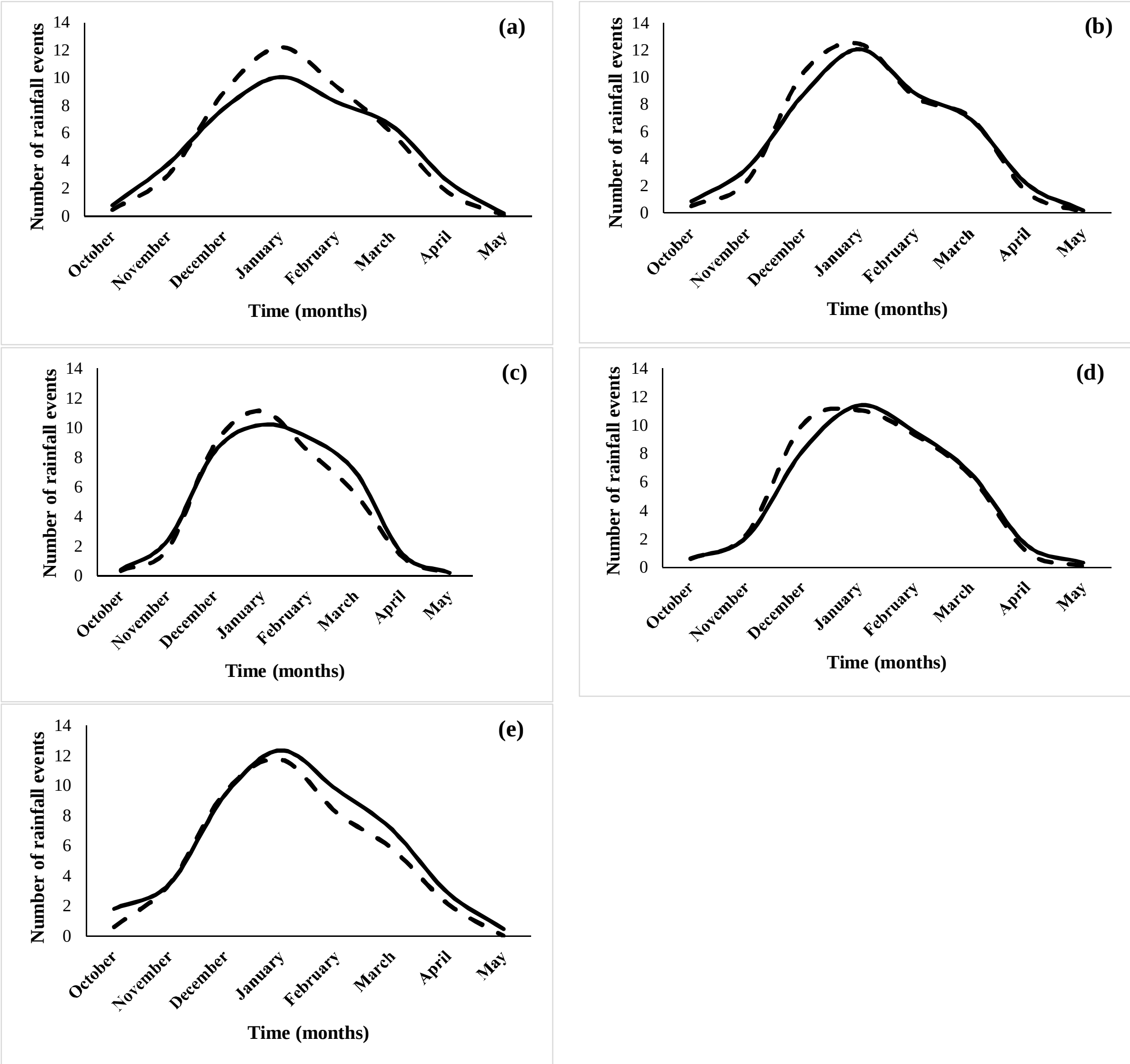

Figure 4-6: Number of rainfall events per month for the central region of Malawi (a: Bunda; b: Chitedze; c: Kasungu; d: KIA; e: Mchinji). Solid line: 1980 to 1994; dotted line: 1995 to 2009

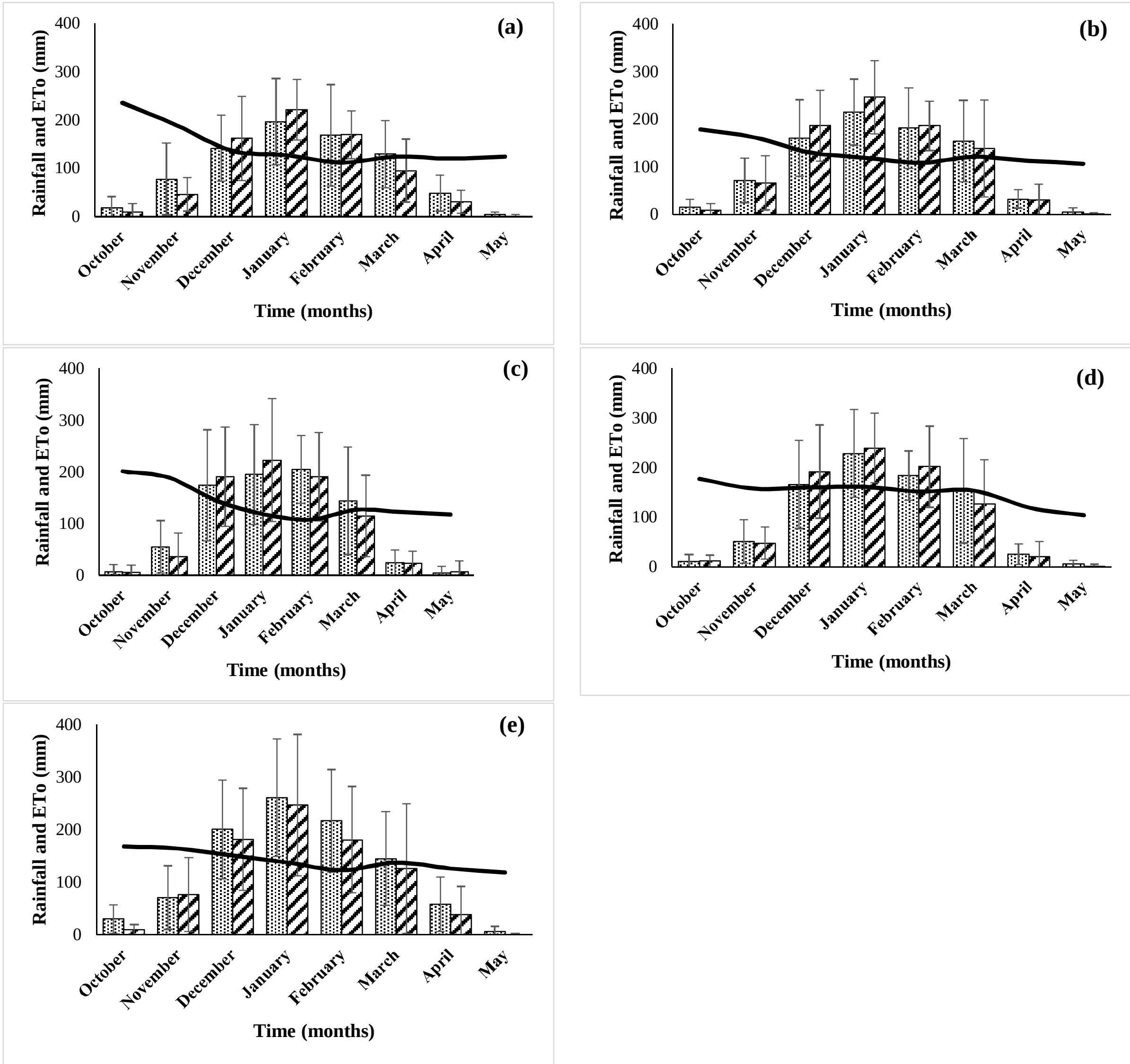

Figure 4-7: Amount of rainfall (bars) and reference evapotranspiration (ET_o) (line) per month for the central region of Malawi (a: Bunda; b: Chitedze; c: Kasungu; d: KIA; e: Mchinji). Dotted: 1980 to 1994; hatched 1995 to 2009. Error bars: standard deviation

Table 4-6 summarises the onset, cessation dates and LGP of the 5 stations in central Malawi in the 2 periods 1980-1994 (earlier) and 1994-2009 (later). The data-set was split into 2 time periods of equal length to evaluate if the increased total and intensity (amount of rainfall per rainy day) of rainfall in January has an effect on the rainfall characteristics. The results show that on average, onset dates have shifted from the last 10 day period of November to the first 10 day period of December between the earlier and later period. There is higher variability in the earlier period than in the latest period as shown by the high (ranging from 5 to 27 days) standard deviation and coefficient of variation (ranging from 6 to 27%). The MK test shows that there is an increasing trend in both the earlier and later periods, with Kasungu and Mchinji showing statistically significant increasing trends in the earlier and later period respectively. The cessation dates for all stations start from the second 10 day period of April for both of the periods considered. Unlike the onset dates, the standard deviation and coefficients of variation are not consistent in displaying higher and lower values. Almost all stations have low CV values (ranging from 5 to 15%), which indicates low variability in terms of cessation of the growing period. On average, the MK test shows a general decreasing trend in both of the periods in almost all stations. The LGP has decreased in all stations from an average of 145 days to ~130 days because of the delay in the onset of the seasons, although this change is not significant at the 95% confidence level in Bunda, KIA and Mchinji. There is also high interannual variability in the LGP that is reflected by high standard deviations and coefficients of variation in all the stations.

Table 4-6: Summary of statistics of onset, cessation dates and length of growing period (LGP) at 5 stations over the period 1980 to 2009 in the central region of Malawi. Earlier: 1980 to 1994; Later: 1995 to 2009.

Statistic	Stations									
	Bunda		Chitedze		Kasungu		KIA		Mchinji	
	Earlier	Later	Earlier	Later	Earlier	Later	Earlier	Later	Earlier	Later
Onset date										
Mean	22-Nov	10-Dec	18-Nov	28-Nov	29-Nov	12-Dec	26-Nov	10-Dec	30-Nov	12-Dec
SD (days)	13	7	11	13	15	5	17	5	27	9
Z_{MK}	-0.16	0.3	0.11	0.25	1.86*	0.4	0.38	0.74	-0.11	1.53*
CV(%)	25	10	23	22	25	6	27	16	47	22
Cessation date										
Mean	22-Apr	21-Apr	20-Apr	18-Apr	19-Apr	25-Apr	20-Apr	19-Apr	20-Apr	19-Apr
SD (days)	26	16	26	22	12	8	24	18	24	18
Z_{MK}	-0.33	0.89	-1.86	-1.19	0	-0.445	0.22	-0.3	-1.64	1.73
CV(%)	13	7	13	11	6	5	12	9	12	15
LGP (days)										
Mean	150	131	153	142	141	134	144	130	144	130
SD	29	38	29	28	20	11	38	20	38	20
Z_{MK}	-0.22	0.4	-1.2	-0.89	-1.2	-0.45	0.11	-1.49	-1.26	0.69
CV(%)	19	13	19	20	14	8	26	15	26	15

ZMK is Mann-Kendall trend test; *is statistically significant trend (α=0.05); SD is standard deviation; CV is coefficient of variation

4.4 Discussion

The objective of this study was to assess the trends of the onset and cessation of the growing period and the LGP in central Malawi for the cultivation of maize. The results indicate that the LGP has been getting shorter in the last 3 decades. This change follows a delaying trend in suitable onset dates and an advancing (early) cessation trend of the growing period in some areas. These characteristics are important as they influence crop production. The results support the notion that the rainfall patterns, which are important for maize production in central Malawi, have shifted. The seasonal amount of rainfall in the region is still the same, but the monthly rainfall and its variation are changing. An implication of this phenomenon is that farmers will have to adopt husbandry practices that can fit in this shortened growing season. However, our study has limitations as it only considered rainfall. Possible trends and shifts in other climatic variables like temperature and other environmental parameters were not considered. The interaction of these factors with rainfall might have an influence on the results presented here. Nonetheless, our assumption was based on the major limiting factor for crop production in the tropics, in this case rainfall.

These results compare well with previous findings of Hachigonta et al. (2008), who reported the seasonal decline between 1979 and 2002 in Zambia, while Hadgu et al. (2013) reported a similar trend of decreasing LGP from 1980 to 2009 in Tigray, north of Ethiopia, from both farmers' perception and meteorological data. Ooms (2012) and Simelton et al. (2013) reported that Malawian farmers' perception in the central region of Malawi was that the start of the rainfall season is shifting from November toward mid-December while cessation is receding toward early April in recent seasons. It is evident from the current analysis that the season is indeed getting shorter, and this has great consequences for food security as problems can arise due to these agro-climatic shifts (Harrison et al., 2011). Farmers have to adjust their cropping calendars and possibly change their cultivars to suit the shorter LGP. This has a negative effect, as these short-season cultivars tend to produce less biomass; hence, total production is lower.

The results of the current study are in contrast with those of Mupangwa et al. (2011) in Zimbabwe and Mugalavai et al. (2008) in Kenya, who found no significant changes in the start, end and LGP. In Malawi, Vrieling et al. (2013) found no significant trends in LGP estimated from NDVI for the 1981-2011 period. This is partly comparable to KIA, Mchinji and Bunda, while Chitedze and Kasungu have significant trends. The source of this discrepancy might be the different approaches or criteria used in identifying the onset of the growing season and the data sets. In this research, we used observed data from stations, while Vrieling et al. (2013) used NDVI, which is spatial and pixel-based. With spatial data, there might be some overestimation of the values. Nevertheless, the authors advocated continuous monitoring of the seasons to detect any shifts if they arise in future.

Malawi's rainfall depends on the position of the ITCZ, which can vary in its timing and intensity from year to year (McSweeney et al., 2010). The country experiences peak rainfall during the month of January, which is associated with the activities of the ITCZ and Congo air mass (McSweeney et al., 2010). Malawi is usually under the active Congo air mass and ITCZ in January, resulting in unstable moist conditions over the country (GoM, 2014). It is the activity of these 2 air masses that results in heavy rainfall in January in most parts of Malawi (GoM, 2014). In recent years (1995 to 2009), there have been more rainfall events in the month of January than in the rest of the months of the rainy season. This means that there is more readily available water for the crop in the month of January than in the rest of the rainy season in this area. The results compare well with those of Simelton et al. (2013), who reported increased monthly rainfall totals for the month of January and significant decreases in monthly rainfall in December, February and April in the same region. The report further states that rainfall intensity became more variable from 1996/97 and significantly increased intensity in January by >80 mm. This result is in line with observations made by Twomlow et al. (2006) that characteristics of growing seasons are influenced by other factors such as rainfall distribution in additional to total rainfall and onset of the rains. Adiku et al. (1997) also stated a stronger influence of the distribution and reliability of rainfall during the growing season on the characteristics of the growing period than of total rainfall.

The results should be taken cautiously, bearing in mind that only 30 years of data were used according to availability while rainfall in East Africa is characterised by a cyclic oscillation that may not coincide with a 30-year period. If long-term data series would have been taken (which were not available for the study area) a number of cyclic oscillations of rainfall would probably have been observed as has been reported for the region. Among others Taye and Willems (2012) have previously reported cyclic oscillations in rainfall of eastern Africa after using long term rainfall data. All this implies that the trends that were found in our study, might be characteristic for a specific period within one cyclic oscillation only. Nevertheless, the presented results are sound as the period under study is relevant for crop production this region.

The large amounts of rainfall in January pose a threat to crop production. There is danger of waterlogging in the fields, which can lead to yield reduction through anaerobic stress in the roots. The extra water can also lead to soil erosion through surface runoff in the absence of soil conservation structures. The water will be lost through runoff, which takes away plant nutrients and loosens topsoil. The use of small ponds deliberately constructed within or adjacent to the field to harvest this extra water is suggested as a control measure. This construction might also in the long term control incidences of soil erosion as more water will be contained in these ponds, and hence, there will be less runoff. The use of field ponds has been a success in northern Ethiopia (Wondumagegnehu et al., 2007) where the growing season is too short and the collected water in the ponds is used for irrigation after cessation of the rains to meet the crop water requirements at the end of the season. However, this proposition comes with a price in that farmers have to be prepared to lose part of the fields to have the ponds constructed, and also that it requires additional costs in labour. This study showed that ET_o is higher than the rainfall amounts in the months of March, April and May, which means that there is water stress during these months. The most critical month is March, as the maize crop is usually still at the grain-filling stage. There is a danger of yield reduction if there is a prolonged water stress during this sensitive growth stage. If the water stored in ponds is used to cover for this period, yield losses will be minimised.

The variability in the onset and cessation of the growing period and consequently the LGP was expected because the rainfall in this region is usually considered variable (Vincent et al., 2013). These variations in the rainfall characteristics were expected as southern Africa is characterised by seasonal and within season rainfall variability. Substantial decadal to multi-decadal summer rainfall variability in southern Africa was reported by Tadross et al. (2005). The interseasonal variability of the rainfall in southern Africa was also reported by Tadross et al. (2009) and Hachigonta et al. (2008), which confirms these findings for Malawi's central region. The inter-annual variability of Malawi rainfall is strongly influenced by the position of the ITCZ and Indian Ocean sea surface temperatures, which can vary from one year to another due to variations in patterns of atmospheric and oceanic circulation, with El Niño Southern Oscillation as the main cause (Hoerling et al., 2006; Lyon and Mason, 2007, 2009; McSweeney et al., 2010). McSweeney et al. (2010) emphasised the difficulty in predicting the influences of El Niño Southern Oscillation on the climate of Malawi by observing that Malawi sits between 2 regions of opposing climatic response to El Niño. Eastern equatorial Africa tends to receive above-average rainfall in El Niño conditions, whilst south-eastern Africa often experiences below-average rainfall. The opposite response pattern occurs in La Niña episodes. The response of climate in each of these 2 regions, and the extent of the area affected, varies with each El Niño or La Niña event, causing mixed responses in Malawi. Therefore, conflicting results regarding the onset, cessation and consequently LGP were expected due to these atmospheric activities. The average onset dates are similar among stations in the 2 periods but with high standard deviations, which suggests the complexity of effective decision making related to planting dates and crop management. There is no stable planting date or window in this area, hence the need for further research to estimate the probabilities of planting windows with predictive models. The high coefficient of variation in LGP follows the pattern of the onset and cessation dates, hence decision making regarding the cropping calendar, cropping pattern and all crop-husbandry practices should be taken cautiously.

The results of this study provide insight into changes in the growing season with reference to the staple food in Malawi, maize. Since most of the smallholder farmers have limited access to agricultural technologies such as fertilizer, pesticides and improved seed, the yields have remained stable at <1 t ha^{-1} (Wiyo et al., 1999). Swift changes are needed to the local farmer practices to deal with the identified shortening of the LGP. Farmers need to adjust their current practices. One of the most widespread strategies for dealing with the increasing variability of the onset of rains is to change planting dates and to use staggered planting. These can take care of the false starts that occur at the start of the rainy season. This would also lessen the exposure of the young plants to early dry spells that occur during the early part of the growing season. Planting maize cultivars (hybrids) that have a shorter growth cycle than the cultivars traditionally used can be another potential adaptation strategy. Although local cultivars are favoured due to their pest-resistance and grain texture, the use of early maturing drought-tolerant cultivars can be beneficial as they grow quickly and can use the available moisture in a short time. These strategies give a relatively safe approach to food production.

4.5 Conclusion

Analysis of the characteristics of the growing season in central Malawi has shown significant changes in the onset, cessation and LGP. There is a clear delayed onset and advanced cessation in some stations and shorter LGP with time within the period considered (1980 to 2009). This pattern requires introduction of crop cultivars with a shorter growing cycle in this region so that the crops can reach maturity without suffering water stress. It also calls for timely preparation of any related crop-husbandry activities before and even during the growing period to realise good harvests. Although the seasonal rainfall amount in Malawi showed no particular trends, there was greater rainfall in January recently (1995 to 2009) compared to earlier periods (1980 to 1994). It is also noted that the last months in the growing period showed a decline in the total rainfall and high evapotranspiration, which can often lead to crop water stress. These findings are essential for the smallholder farmers in central Malawi as the farmers can use the proposed strategies to identify the best maize cultivars that can do well in the short growing periods. With the changes in climate in this region, there is a need to invest in soil and water management technologies suitable for smallholder cropping systems to address the obvious and possible impacts of climate change in southern Africa.

Chapter 5
Future Climate Downscaling

5.1 Introduction

Climate change refers to change over long time in the state of the climate that can be identified (for example, using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer (IPCC, 2007). The change in the climate mean state within a certain time period is referred to as climate variability which can be more detrimental than the climate change (IPCC, 2007). Both climate variability and change have potentially significant adverse implications on the hydrological cycle and water resources (Fatichi et al., 2011), and on crop production (IPCC, 2014).

The climate system affects all aspects of the hydrologic cycle, as it is one of the most vulnerable systems. Changes in variability, spatial patterns and seasonality of rainfall and temperature have an effect on soil moisture, and general hydrology of a catchment. To develop strategies and make informed decisions about future water allocation for different sectors and management of available water resources, there is need of climate change information that can directly be used to study impacts through modelling.

Information about future climate and its change is commonly inferred from General Circulation Models (GCMs). However, they have an important drawback: their spatial resolution is too coarse (a grid box covers more than 40,000 km^2) to be used directly in local studies (Fatichi et al., 2011). Thus, there is a need for downscaling the GCM output to a very fine resolution, sometimes even to station scale. The downscaling methodologies developed to date can be broadly categorized as statistical and dynamical. Both dynamic and statistical downscaling have been attempted in recent studies (Fowler et al., 2007; Prudhomme et al., 2002; Varis et al., 2004). In this research, the focus is on statistical downscaling in which inferences between GCMs realisations and climate characteristics at local scale are made, for example through a stochastic weather generator (Fowler et al. (2005); Kilsby et al. (2007); Semenov and Barrow (1997); and Semenov and Porter (1995b)). The use of stochastic weather generators is very popular because they are computationally less demanding, simple to apply and can provide station scale climate change information (Dibike and Coulibaly, 2005; Kilsby et al., 2007).

Weather generators are statistical models used to generate a long synthetic series of data, fill in missing data and produce different realizations with the same data (Wilks and Wilby, 1999). They employ random number generators and use the observed time series of a station as input. These models have been extensively used in agricultural studies of crop productivity and water resources engineering (Dubrovský et al., 2004; Hartkamp et al., 2003; Mavromatis and Hansen, 2001; Riha et al., 1996; Semenov and Porter, 1995a; Vanuytrecht et al., 2014b). Weather generators can generate meteorological variables at daily or annual time scales on the basis of empirical statistical models. In these cases, statistical properties and correlations among variables are directly inferred from observed data (Fatichi et al., 2011). Precipitation is typically considered to be the primary variable. Other climate variables (or their residuals, since the mean and variance are typically removed) are generated by means of regression equations in correlation to the rainfall data (Fatichi et al., 2011).

The main objective of this chapter was to generate local-scale climate projections for central Malawi which will be used as input in a model for assessing the effect of future climate change on maize and sorghum production in Malawi (Part IV). This study focussed on central Malawi, and used for the purpose a single station in central Malawi, which had a long record of daily climate data.

5.2 Materials and methods

5.2.1 Historical climate

A set of 43 years (1970 – 2013) of observed daily rainfall, maximum and minimum temperature data for Chitedze meteorological station (13.97° S, 33.63° E, 1149 masl) was collected from the Malawi meteorological services department.

5.2.2 Future climate

Climatic change factors from 15 GCMs (Table 5-1) from the Coupled Model Intercomparison Project phase 3 (CMIP3) (Meehl et al., 2007) were used. The GCM output was downscaled to local-scale future data following two distinct methodologies, i.e. following the self-organising maps (SOM) approach (Hewitson and Crane, 2006) by the University of Cape Town-Climate Systems Analysis Group (UCT-CSAG) and applying the stochastic weather generator LARS-WG (Semenov and Stratonovitch, 2010).

- The dataset from UCT-CSAG originated from output of nine GCMs forced with the Special Report on Emissions Scenarios (SRES[2]) A2 emission scenario. The data was downscaled to the KIA station, which is about 20 km from Chitedze by UCT-CSAG using the self-organising maps (SOMs) approach, described in detail by Hewitson and Crane (2006). The dataset included generated baseline data (1961-2000) and projections for the future (2046-2065). The SRES A2[3] scenario was the only scenario being used by UCT-CSAG at the time this data was being generated.

- Another dataset, originating from output of 15 GCMs forced with the SRES A1B[4] emission scenario was generated using a stochastic weather generator, LARS-WG (Semenov and Stratonovitch, 2010). The A1B scenario was chosen here because it has the same [CO_2] for the 2050s hence there was not much difference between the two. The period chosen to compare the climatic changes were the end of the 20th century (baseline: 1970-2013) and the middle of the 21st century (2046-2065). The baseline period for this dataset differed from the baseline period for the UCT-CSAG dataset because of data availability during the data processing time. A stochastic weather generator was selected because of its ability to generate long data series which allows

2 The SRES scenarios were developed by the IPCC. Several greenhouse gas (GHG) emission scenarios were developed following different driving forces and the highly uncertainty of the future concentration of the GHGs. These scenarios portrays alternative images of how the future might evolve. The scenarios are grouped into four families (following assumptions of the storylines (driving forces used). There are four families, **A1**, **A2**, **B1** and **B2**. Scenarios in a family follows the modelling approach used hence they can differ within a family (Nakicenovic et al., 2000).

3 The key assumptions are a very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development.

4 The key assumptions are a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality.

inclusion of climate temporal variability and extremes hence suitable for risk assessment (Semenov, 2007; Semenov and Porter, 1995b; Wilks and Wilby, 1999). The generation of this weather dataset is described in detail in the following paragraphs.

Table 5-1: Global Climate Models (GCMs) from Coupled Model Inter-comparison Project Phase 3 (CMIP3; Meehl et al., 2007) that were used in this research

Model acronym used	**Research centre**	**Model full name**	**Approach used**	**Grid resolution**	**Reference**
BCM2	Bjerknes Centre for Climate Research	BCM2.0	L[1]	1.9 x 1.9°	Déqué et al. (1994)
CGMR	Canadian Centre for Climate Modelling and Analysis	CGCM33.1(T47)	L, U[2]	2.8 x 2.8°	McFarlane et al. (1992)
CNCM3	Centre National de Recherches Meteorologiques	CNRM-CM3	L, U	1.9 x 1.9°	Déqué et al. (1994)
CSMK3	Commonwealth Scientific and Industrial Research Organisation	CSIRO-MK3.0	L, U	1.9 x 1.9°	Gordon et al. (2002); CSMD (2005)
FGOALS	Institute of Atmospheric Physics	FGOALS-g1.0	L	2.8 x 2.8°	Wang et al. (2004)
GFCM21	Geophysical Fluid Dynamics Laboratory	GFDL-CM2.1	L, U	2.0 x 2.5°	Anderson et al. (2004)
GIAOM	Goddard Institute for Space Studies	GISS-AOM	L, U	3 x 4°	Russell et al. (1995)
HadCM3	UK Meteorological Office	HadCM3	L	2.5 x 3.75°	(Gordon et al., 2002; Pope et al., 2000)
HADGEM	UK Meteorological Office	HadGEM1	L	1.3 x 1.9°	(Martin et al., 2006; Ringer et al., 2006)
INCM3	Institute for Numerical Mathematics	INM-CM3.0	L	4 x 5°	Galin et al. (2003)
IPCM4	Institute Pierre Simon Laplace	IPSL-CM4	L, U	2.5 x 3.75°	Hourdin et al. (2006)
MIHR	National Institute for Environmental Studies	MRI-CGCM2.3.2	L, U	2.8 x 2.8°	Hasumi and Emori (2004)
MPEH5	Max-Planck Institute for Meteorology	ECHAM5-OM	L, U	1.9 x 1.9°	Roeckner and Arpe (1996)
NCCCS	National Centre for Atmospheric Research	CCSM3	L	1.4 x 1.4°	Collins et al. (2006)
NCPCM	National Centre for Atmospheric Research	PCM	L, U	2.8 x 2.8°	(Kiehl et al., 1998; Kiehl and Gent, 2004)
MIUB	Meteorological Institute of the University of Bonn (Germany), Meteorological Research institute of KMA, Model and Data group at MPI-M (Korea)	ECHO-G	U	3.8 x 3.8	Legutke and Voss (1999)

L[1] is LARS-WG and U[2] is UCT-CSAG approaches used respectively

5.2.2.1 Brief description of Self-Organising Maps (SOM)

A self-organizing map (SOM) is defined as a data description and visualization tool that extracts and displays the major characteristics of the multidimensional data distribution function (Hewitson and Crane, 2006). In their study, SOMs were typically depicted as a two-dimensional array of nodes (although other topologies are possible), where each node was described by a vector representing the mean of the surrounding points in the multidimensional data space. In first application respect, SOMs were said to be similar to a 'fuzzy' clustering algorithm in which there are no distinct boundaries between groups, and individual data points could contribute to the definition of more than one group. In the second applications SOMs could be analogous to obliquely rotated nonlinear empirical orthogonal functions (EOFs) or a projection of the n-dimensional data space onto a two-dimensional array of generalized modes (Hewitson and Crane, 2006). SOMs have been used in several studies such as in Hewitson and Crane (2002) who reported on the potential applications to synoptic climatology, Hewitson (2003) on precipitation regimes and Hewitson and Crane (2005) on interpolation schemes of SOMs. Other reported studies on the application of SOMs include climate classification (Malmgren and Winter, 1999) and examining synoptic circulation changes in GCM perturbation experiments by Hudson (1998).

5.2.2.2 Future climate downscaling using self-organising maps

The data for central region (Malawi) was downscaled using the SOMs according to Hewitson and Crane,(2006). These SOMs were derived from an iterative training procedure which uses two-dimensional array of nodes, each defined by a reference vector of length n. For a (n×m) data set where n is the number of variables and m is the number of observations. The observational vector was compared to each of the node reference vectors in the SOM (typically using Euclidean distance as the measure of similarity). The reference vector was adjusted slightly in the direction of the observational vector by a user-determined factor that represents the ‘learning rate’. Too large a learning rate may lead to an unstable solution, while a small learning rate takes longer to converge on a solution.

5.2.2.3 Brief description of LARS-WG

LARS-WG is a stochastic weather generator that can be used for simulating weather data at a single site under both current and future conditions (Semenov and Stratonovitch, 2010). It uses observed daily weather data for a given site to compute a set of parameters for probability distributions of weather variables as well as well as correlation between them. The computed set of parameters are used to generate synthetic time series of arbitrary length by randomly selecting values from appropriate distributions. For the generation of future data, the parameters of the distributions for a site are subsequently perturbed with the projected changes derived from GCM runs to finally generate a daily climate scenario of the future for a specific site. The change factors are calculated as relative changes for precipitation, and absolute changes for minimum and maximum temperature. Distributions of dry and wet series and temperature variability are not adjusted (Semenov and Stratonovitch, 2010). LARS-WG has some weaknesses which include underestimating extremes because events outside those present in the observations cannot be reproduced (Fowler et al., 2007), and over dispersion and underrepresentation of precipitation persistence resulting in potential underestimation of inter-annual variance of monthly precipitation sums or temperature means (Kim et al., 2012; Wilks and Wilby, 1999). It also assumes constant relations between atmospheric and local climatic variables in the future (Vanuytrecht et al., 2014b; Willems et al., 2012), which obviously might not be the case.

5.2.2.4 Stochastic weather generation process in LARS-WG

The process of generating synthetic weather data in LARS-WG can be divided into three distinct steps, which are calibration, validation and climate scenario generation. Model calibration is done by analysing observed weather data (for example, precipitation and maximum and minimum temperature) to determine their statistical characteristics, and next generating synthetic weather data that corresponds to the observed statistics. Model validation comprises the evaluation of the performance of the weather generator at the study site by comparing the statistical characteristics of synthetic to observed historical weather data. Kolmogorov-Smirnov, t- and F-tests are performed for this purpose. After validation, future climate change projections can be generated based on GCM output for three periods (2020s, 2050s and 2090s). More detailed description of the modelling procedure can be found in Semenov and Barrow (1997), Semenov and Doblas-Reyes (2007) and Semenov and Stratonovitch (2010).

5.2.2.5 Future climate downscaling using LARS-WG

GCMs (15 A1B) from the CMIP3 project with resolution of 200-300 km (Meehl et al., 2007) were used. These are the GCMs which are currently present in LARS-WG version 3.5. Fifteen data sets of daily weather (precipitation, minimum and maximum temperature) were generated with LARS-WG. Local climate scenarios for the future were generated by applying signals from each one of the climate models to the generated historical data to produce 100 years of stochastically downscaled future weather data. Thus 15 sets of 100 years of future weather data were generated. These 100 years were not cumulative in time but one by one representative for the whole period. The number of years was chosen to ensure long simulation series for adequate risk assessment. To present the range of projected climate changes, the median scenarios were plotted in boxplots and compared with the median baseline weather. Relative change percentages in rainfall and absolute difference in temperature between baseline and future climate were used for comparison.

5.2.3 Evaporating power of the atmosphere (ET_o)

The reference evapotranspiration was computed with the help of ET_o calculator by considering the generated minimum and maximum air temperature for each year and each GCM. Air humidity was derived from minimum air temperature by assuming that it is a good proxy of the dew point temperature. Radiation data was derived from the air temperature difference method as described in Allen et al. (1998). Wind speed was assumed to be at 2 m s^{-1}.

5.2.4 Cumulative distribution of daily precipitation

Before the future weather data of both datasets were used, the cumulative distributions of the generated future rainfall data were compared with the cumulative distribution of the historical observed rainfall data to check whether typical seasonal rainfall patterns (which were assumed to remain similar in the future) could be imitated by the models (LARS-WG and the approach of UCT-CSAG). A growing season with similar total rainfall for the three data sets was selected as an example.

5.2.5 Statistics

Two statistical tests were applied to compare generated versus observed, and generated baseline versus future climate variables, which is the non-parametric two sample Kolmogorov-Smirnov (KS) test for comparison of probability distributions, and unpaired t-tests for comparison of means. KS-tests were applied to compare the seasonal distributions of dry and wet days, and the monthly distributions of daily precipitation, minimum and maximum temperature with the null hypothesis of equal distribution being tested. T-tests were applied to compare monthly means of daily precipitation, minimum and maximum temperature, and the null hypothesis of equal means was tested. For identifying significant effects, all tests were done at 1% level of significance ($p < 0.01$). It has to be noted that these statistical tests were done only on data which used LARS-WG approach. The UCT-CSAG approach data provided (generated climate data) was only for a single year hence it was difficult to perform a number of statistical analyses.

5.3 Results and discussion

5.3.1 Validation of historical data

Table 5-2 through to 5-4 shows the KS-test results for LARS-WG approach for seasonal wet and dry series, mean daily precipitation of each month and mean monthly temperature distributions. The letter “n” in the tables represents the number of test carried. The results of the KS-tests showed that the generated seasonal wet and dry series distribution did not differ from the observed historical distribution (Table 5-2). The hypothesis of no significant difference between monthly precipitation and temperature means of generated and historical data was confirmed by t-tests (the results are shown in Annex III). However, KS- and t-tests showed significant difference for generated daily precipitation for the months of June and July (Table 5-3). This is because in these months there is usually no or trace rainfall recorded in the area. Since this research focusses on the main rainy season in Malawi (Nov to April), the results are assumed not to have any impact or cause errors in the simulation of crop growth. For temperature, there was no significant differences observed (Table 5-4).

Table 5-2: KS statistics for wet/dry series precipitation distribution for central Malawi

Season	Wet/Dry	n	KS	P-Value
DJF	wet	12	0.03	1
	dry	12	0.197	0.7144
MAM	wet	12	0.03	1
	dry	12	0.151	0.937
JJA	wet	12	0.03	1
	dry	12	0.087	1
SON	wet	12	0.101	0.9995
	dry	12	0.066	1

Table 5-3: KS statistics for mean daily precipitation distribution of each month for central Malawi

Month	n	KS	P-Value
January	12	0.055	1
February	12	0.104	0.9992
March	12	0.055	1
April	12	0.045	1
May	12	0.303	0.1992
June	12	0.567	0.0006
July	12	0.478	0.0064
August	12	0.261	0.3593
September	12	0.218	0.5895
October	12	0.038	1
November	12	0.057	1
December	12	0.057	1

Table 5-4: KS statistics for air temperature distribution for central Malawi

Month	n	Minimum Temperature		Maximum Temperature	
		KS	P-Value	KS	P-Value
January	12	0.053	1	0.053	1
February	12	0.053	1	0.105	0.9991
March	12	0.158	0.9125	0.106	0.9989
April	12	0.053	1	0.053	1
May	12	0.106	0.9989	0.211	0.631
June	12	0.053	1	0.053	1
July	12	0.053	1	0.106	0.9989
August	12	0.106	0.9989	0.106	0.9989
September	12	0.053	1	0.106	0.9989
October	12	0.053	1	0.053	1
November	12	0.158	0.9125	0.105	0.9991
December	12	0.053	1	0.053	1

Worth noting between the two approaches is that LARS-WG outputs fits well with observations unlike UCT-CSAG outputs. The difference in downscaling approaches attributes to this difference in fitting of the distribution between the two approaches. Figures 5-1 through to 5-4 show observed and generated historical precipitation and temperature using the two approaches.

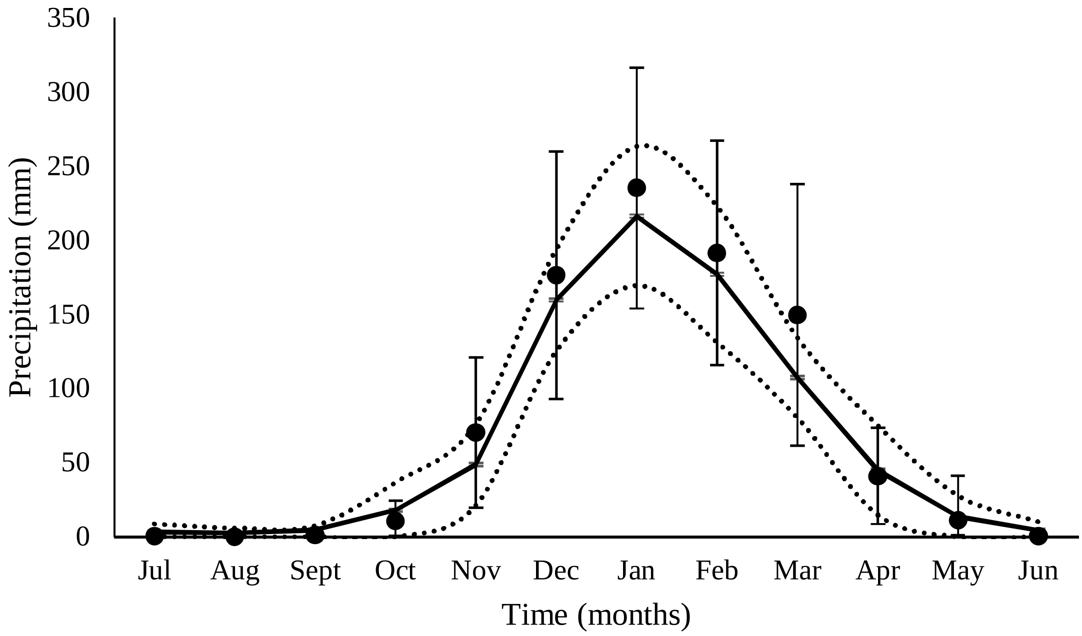

Figure 5-1: Observed (symbols) and generated (full line) mean monthly precipitation for the baseline period of central Malawi using UCT-CSAG approach. Error bars and dashed lines indicate standard deviation for 43 years of observed and generated data, respectively.

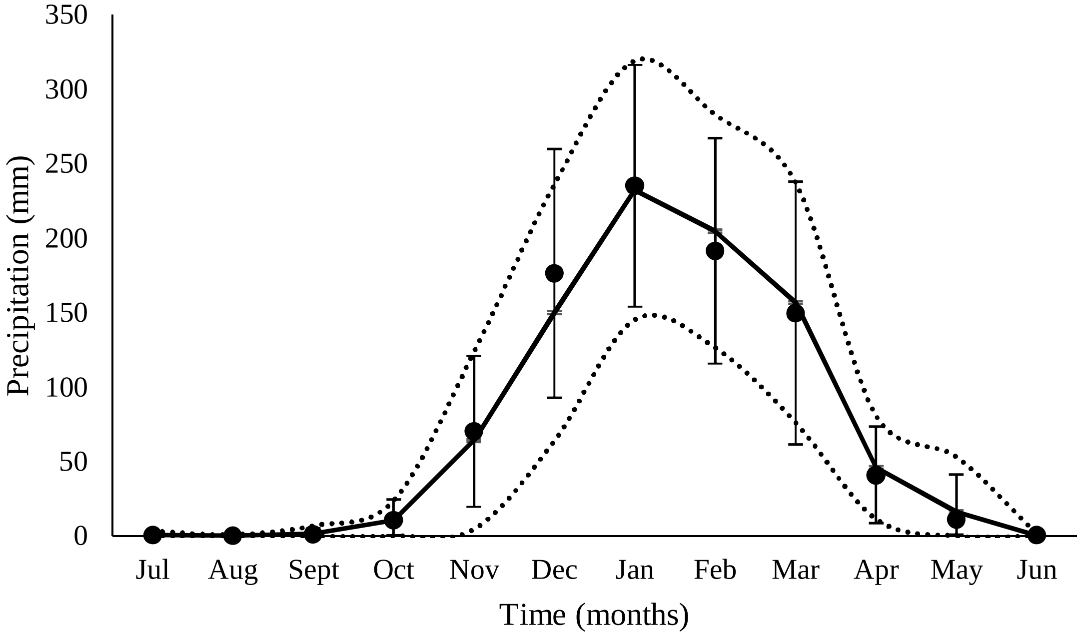

Figure 5-2: Observed (symbols) and generated (full line) mean monthly precipitation for the baseline period of central Malawi using LARS-WG. Error bars and dashed lines indicate standard deviation for 43 years of observed and 100 years of generated data, respectively.

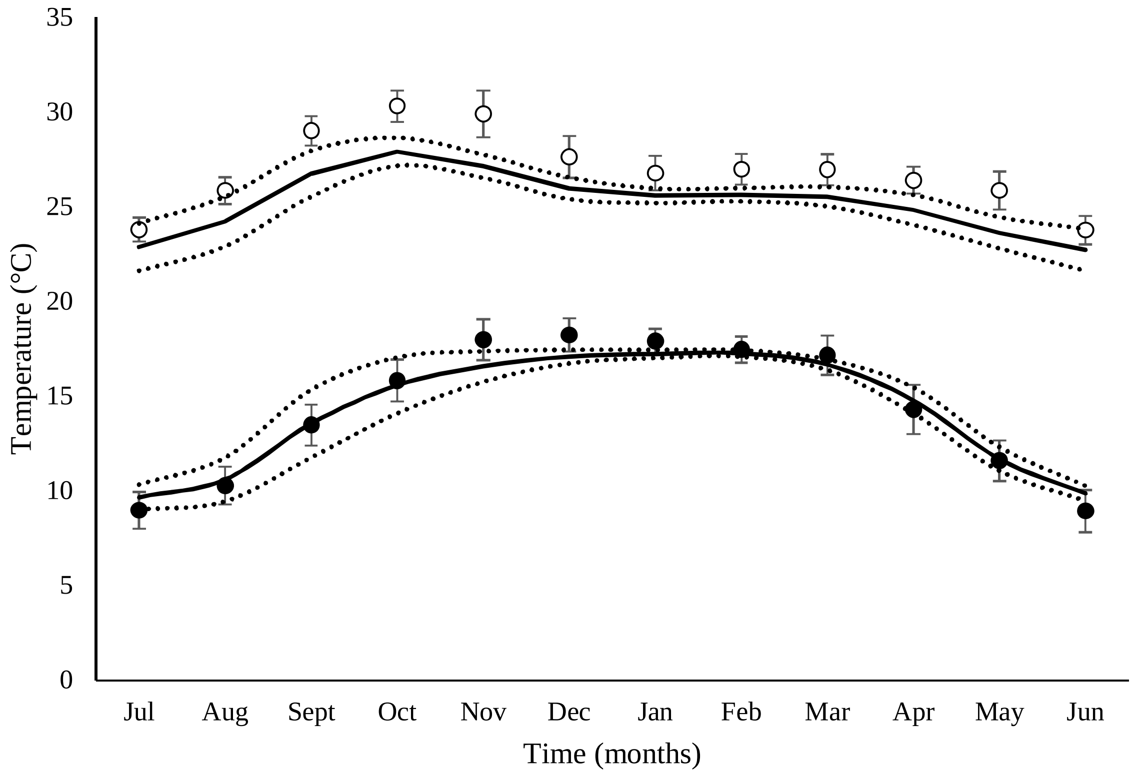

Figure 5-3: Observed maximum (open symbols) and minimum (solid symbols) mean monthly temperatures for the baseline period of central Malawi UCT-CSAG approach. Error bars and dashed lines indicate standard deviation for 43 years of observed and generated data, respectively.

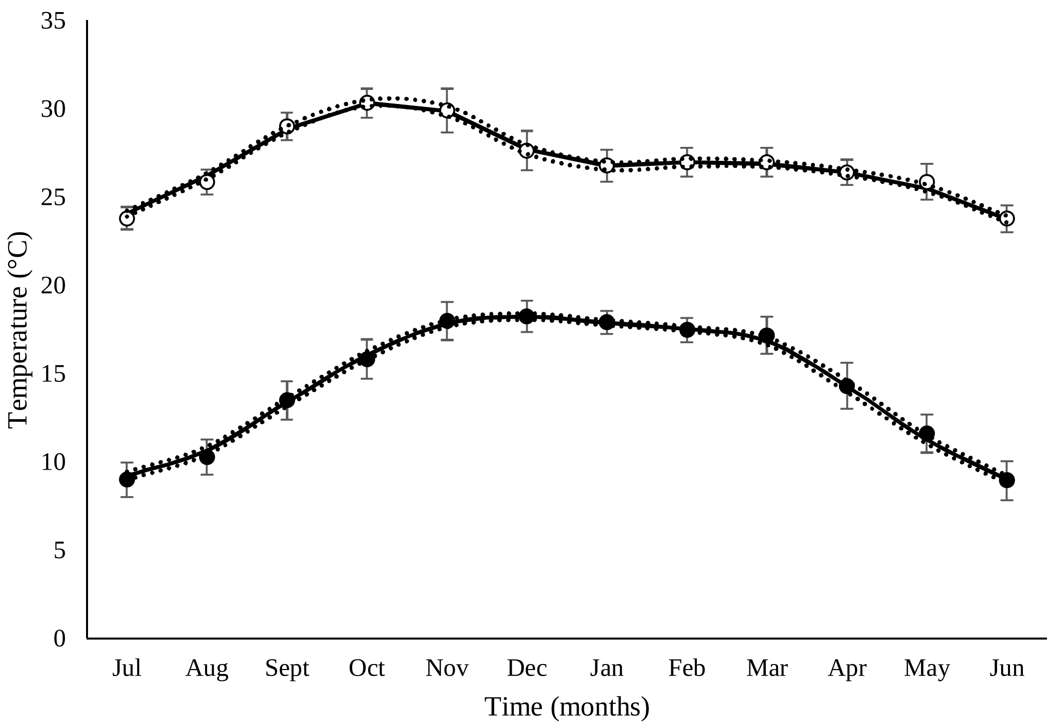

Figure 5-4: Observed maximum (open symbols) and minimum (solid symbols) mean monthly temperatures for the baseline period of central Malawi using LARS-WG. Error bars and dashed lines indicate standard deviation for 43 years of observed and 100 years of generated data, respectively.

The generated data from the two approaches followed the general distribution of precipitation and temperature typical of the area. The mean monthly precipitation and temperature are very well represented. However comparing the two methods shows that LARS-WG generated the data better than UCT-CSAG approach. The generated rainfall by LARS-WG fits well with observed data while UCT-CSAG approach, was underestimating rainfall. LARS-WG also shows an excellent performance in representing the observed standard deviation of mean monthly precipitation. Similarly, for temperature, LARS-WG performed better than UCT-CSAG. There is a general underestimation of maximum temperature by UCT-CSAG. Although the generated (downscaled) data is well distributed and follows the general pattern of the area, LARS-WG performed better than UCT-WG hence it was assumed successful and permitted the use of LARS-WG for generating future climate data for central Malawi.

5.3.2 Cumulative rainfall check

Cumulative future rainfall (and thus seasonal rainfall patterns) from the UCT-CSAG approach and from LARS-WG were plotted against historical observations in Figure 5-5. LARS-WG generated data mimic the typical pattern of cumulative rainfall in Lilongwe as represented by the historical observations, i.e. a unimodal rainfall pattern usually characterized by dry spells within the growing season. Cumulative rainfall plots usually have steps to indicate these breaks in rainfall. The generated data from the UCT-CSAG produced a very smooth graph which means that rainfall is smoothly distributed over the season with rain every day. This is not a realistic rainfall pattern, hence data from UCT-CSAG cannot be used further in this research (part IV).

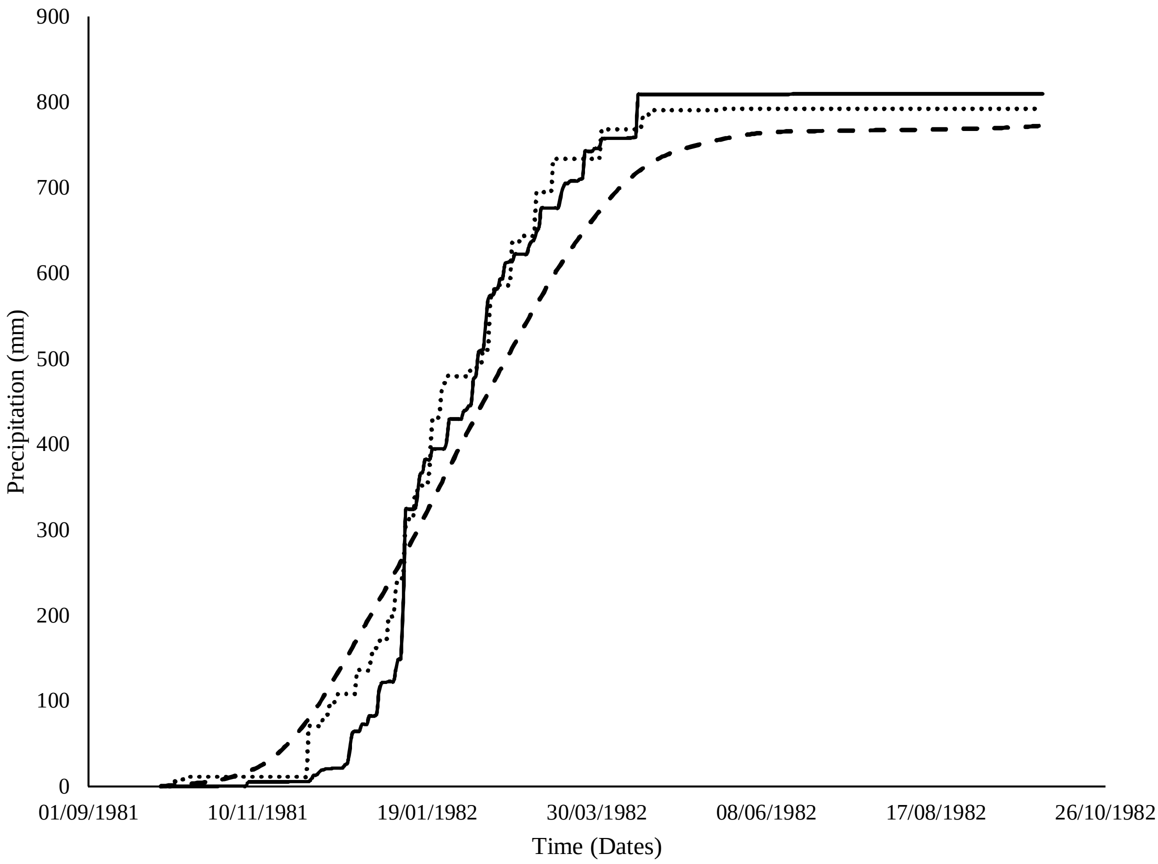

Figure 5-5: Comparison of cumulative rainfall of a typical growing season in central Malawi with similar total rainfall. Historical observations of 1981/82 growing season (dotted line), and CNCM3 GCM output of SRES A2 scenario from LARS-WG (solid line) and UCT-CSAG (dashed line).

5.3.3 LARS-WG future climate scenarios

5.3.3.1 Precipitation

Differences (relative change) between the generated baseline and CMIP3 projections of monthly precipitation are shown in Figure 5-6. The box plots illustrates the range of uncertainty in climate change as projected by the multi-model ensemble. SRES A1B projected increase in summer rainfall and decrease in winter rainfall. Three models (CGMR, CSMK3 and MIHR) show positive relative change in rainfall (ranging from 1.4 to 5%). The rest 12 models present a decrease in rainfall with a negative relative change in rainfall (ranging from -0.8 to -11.5%) when compared to the baseline. These differences in models illustrate the characteristic of rainfall in this region hence there is high uncertainty in rainfall projections in this region. The differential behaviour of climate models has been reported in climate change reports of mixed responses of models in southern Africa (Tadross et al., 2009). These researchers reported an increase in late summer precipitation in countries in south eastern Africa, like Malawi. Zinyengere et al. (2014) reported mixed response of climate models forced with SRES A2 scenarios on precipitation projections for Lilongwe.

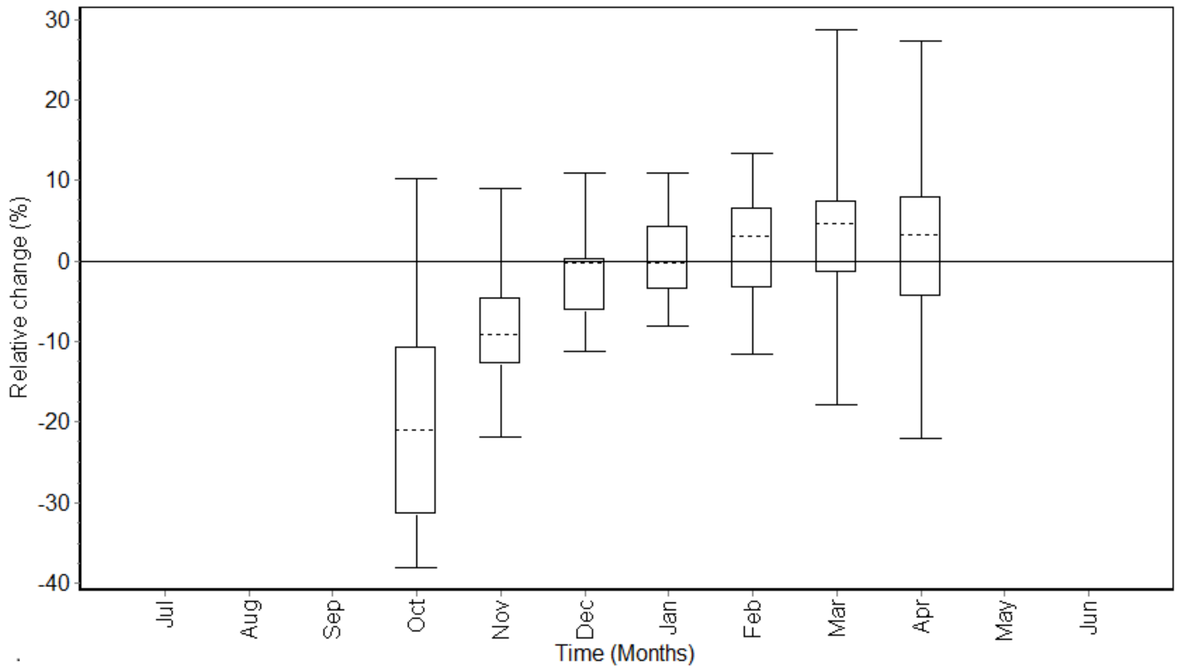

Figure 5-6: Relative change in mean monthly precipitation between the generated 2050 climate projections and the baseline. Boxplots represent uncertainty in projections from 15 GCMs. Box boundaries indicate 25- and 75-percentiles, the dotted line within the box is the median, and whiskers indicate the 10- and 90-percentiles. The straight line indicates no change from baseline to future scenario

The average difference between the generated and historical seasonal rainfall is limited to -3%. The range varies from -11.5 to 4.9% (Table 5-5)

Table 5-5: Future seasonal rainfall projections and relative change as compared to the historical average (1970-2007)

GCM	Total rainfall (mm)	Relative change (%)
MIHR	946	4.9
CSMK3	936	3.7
CGMR	916	1.4
BCM2	896	-0.8
NCCCS	892	-1.2
NCPCM	888	-1.7
INCM3	885	-2
FGOALS	882	-2.3
IPCM4	874	-3.2
CNCM3	866	-4.1
HadCM3	866	-4.1
GIAOM	842	-6.8
HADGEM	827	-8.4
MPEH5	817	-9.5
GFCM21	799	-11.5
Average	875	-3.0
Historical (1970-2013)	903	

5.3.3.2 Temperature

Absolute differences between the generated baseline and CMIP3 projections of mean monthly temperature are shown in Figure 5-5. The box plots illustrates the range of uncertainty in climate change as projected by the multi-model ensemble. All models agreed on a future increase in temperature. A median temperature increase of around 1.8°C is observed, but individual model projections divert between 1°C to just above 2°C for February as an example. These results compare well with what Zinyengere et al. (2014) found for Lilongwe. The researchers noted a similar projected increase in temperature using SRES A2 scenarios.

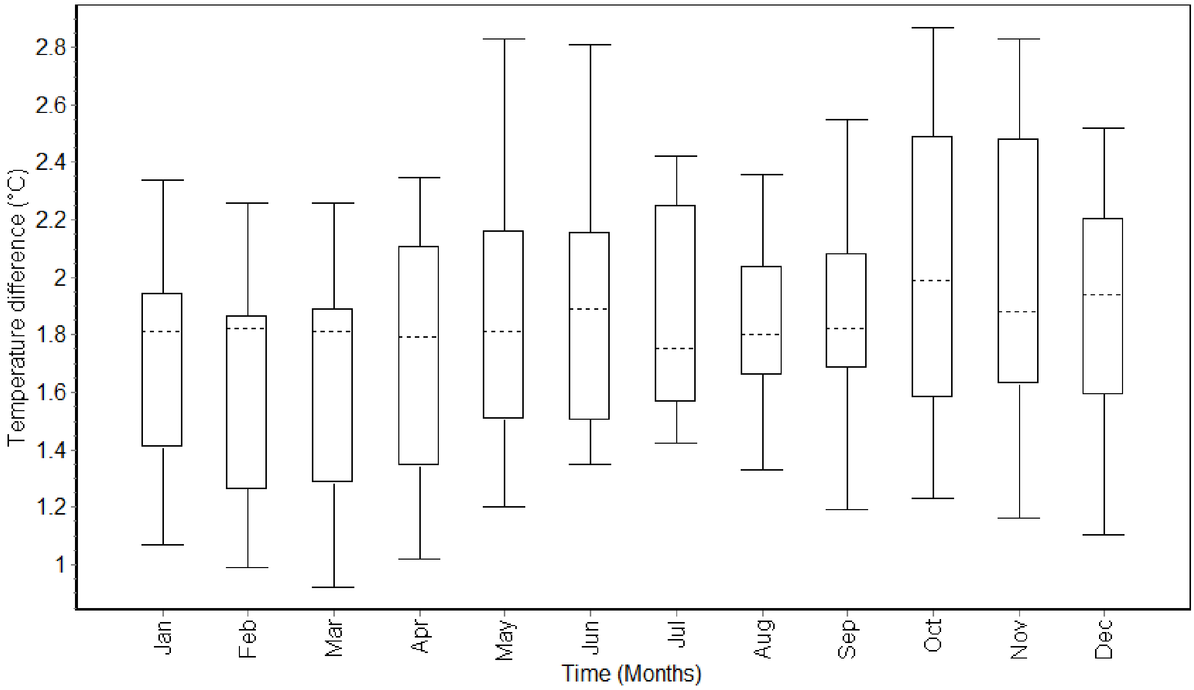

Figure 5-5: Difference in monthly mean temperature between the generated 2050 climate projections and the baseline. Boxplots represent uncertainty in projections from 15 GCMs. Box boundaries indicate 25- and 75-percentiles, the dotted line within the box is the median, and whiskers indicate the 10- and 90-percentiles.

5.3.3.3 Evaporating power of the atmosphere (ET_o)

The generated temperature increase of 1.8°C resulted in an ET_o increase of 3.4% (Table 5-6)

Table 5-6: Comparison between generated annual total reference evapotranspiration (ET_o) and historical ET_o (1970-2007)

GCM	ET_o (mm)	Relative change (%)
MIHR	1724	6
MPEH5	1700	4.6
GFCM21	1697	4.4
CNCM3	1694	4.2
HadCM3	1694	4.2
CGMR	1691	4
IPCM4	1691	4
HADGEM	1682	3.4
GIAOM	1677	3.1
INCM3	1666	2.5
FGOALS	1664	2.3
CSMK3	1660	2.1
BCM2	1658	2
NCPCM	1658	2.6
NCCCS	1652	1.6
Average	1681	3.4
Historical (1970-2013)	1658	

5.4 Conclusion

Climate change signals from 15 GCMs were downscaled with the validated LARS-WG to future local weather data. Increase in monthly mean temperatures and increases or decreases in monthly rainfall depending on the month were projected by the multi-model ensemble median for Lilongwe. Differences within the multi-model ensembles represent the uncertainty associated with climate model structure. Data from UCT-CSAG were not representative for the actual weather in the region and considered unsuitable for this study. Therefore, only generated data by LARS-WG will be used further in part IV.

Part III Model

Chapter 6
Crop yield response to soil water and soil fertility stress

6.1 Introduction

The aim of field experiments in this research was (i) to evaluate the effect of different management practices with different fertility levels on crop yield and (ii) to obtain field data for fine tuning and validation of the FAO AquaCrop crop model for Malawian conditions. The model will be used to derive and assess strategies which farmers can implement on their fields to increase crop yields (part IV). The field experiments were conducted in three growing seasons (2010/11 - 2012/13).

6.2 Materials and methods

6.2.1 Study area

The study was conducted at Bunda and Kasinthula in Lilongwe and Shire Valley Agricultural Development Divisions (ADDs), respectively. The soil at Bunda are predominantly red soils classified as ferric Luvisol, with a sandy clay texture and deep water tables (>8 m) (Lowole, 1983; Wiyo, 1999). The soil at Kasinthula is classified as gleyic Vertisols. It is moderately coarse to moderately fine textured developed in the brown sediments of the lower Shire terrace (Kadyampakeni, 2013). The soil is generally well drained sandy clay loam and the measured water table at the experimental station was deep (>5 m).

6.2.2 Experimental design

The field experiments were laid out in a Randomized Complete Block Design (RCBD) with three replications in the 2010/2011 and 2011/2012 seasons for maize and sorghum separately. There were two levels of fertiliser application, full dose (F1) and half dose (F0) according to the recommendations of the government extension service. In the 2012/2013 season, a complete factorial of three cultivars (early, medium and late maturing) (main plot) and two fertilizer levels (F1 and F0) (sub plot) in a split-plot design, replicated three times was used. The layout of the field experiments is presented in Annex II, and this was the same for both maize and sorghum at both sites.

6.2.3 Trial management

The crops were managed according to the guidelines of the Malawi's ministry of agriculture (MoAFS, 2012). The experimental plot size in both sites was 15 m by 15 m to allow for border effects, the harvesting plot of 10 m by 10 m. The plots were spaced 5 m apart. The ridges were constructed using a hand hoe, commonly used by subsistence farmers in Malawi and spaced 0.75 m apart.

Maize was sown one seed per station with planting stations spaced 0.25 m apart. The target planting density was 53,333 plants per hectare. The maize variety used in was SC403 from SeedCo Malawi limited. For sorghum, five seeds were placed in a groove at 2.5 cm deep per planting station also spaced 0.25 m apart. The seeds were thinned to two plants per station when plants were 15 cm high. The targeted planting density for sorghum was 106,667 plants per hectare. The variety used was Pilira 1. The crop characteristics of the cultivars used are presented in Table 6-1 and 6-2 for maize and sorghum respectively. In the third year experiments additional cultivars were used, these include SC 627 and 727 for maize and PN3 and Pilira 2 for sorghum.

Table 6-1: Characteristics of recommended maize hybrid cultivars (Source: MoAFS, 2012)

Area	Suitable maize cultivar	Days to maturity	Potential yield (t ha^{-1})
Low altitude	SC 513	90-130	6
Low to medium altitude	SC 403	100-120	5-6
Medium altitude	SC 627	130-140	8-10
High altitude	SC 727	140-160	15

Table 6-2: Characteristics of recommended sorghum cultivars (Source: MoAFS, 2012)

Area	Suitable sorghum cultivar	Days to maturity	Potential yield (t ha^{-1})
Low to medium altitude	PN 3	90	3
Low to medium altitude	Pilira 1 (SPV 351)[a]	100-115	3.4
Low altitude	Pilira 2 (SPV 475)[a]	110-120	3
Low altitude	Gwiramtima	100-105	2.4-3.5

At sowing, basal fertilizer (23:21:0+4S (N:P:K)) was applied at 100 kg ha^{-1}. Top dressing was applied three weeks after sowing using urea at a rate of 150 kg ha^{-1}. First the grooves around the planting stations or holes which were about 5 cm away from planting stations were made. And the fertilizer was applied into these holes and covered with soils .The actual application was done using a recommended fertilizer application cup number 5 (MoAFS, 2012). The cup contents is equal to the amount of fertilizer if a Coca-Cola bottle top without lining is used. The full cup was used to These application rates (F1:full dose) are recommended by the extension service (MoAFS, 2012) although they are relatively low when compared to the optimal rate of 200 kg ha^{-1} N recommended by (FAO, 2004). These rates in nutrients per hectare translates into N: 92 kg/ha and P: 21 kg/ha of P_2O_5. For half dose (F0) treatments; the same type of fertilizers were used. The application rate for basal dressing at sowing was 50 kg ha^{-1}, while for top dressing was 75 kg ha^{-1}. All other cultural practices were the same for all experimental plots as recommended by the extension service (MoAFS, 2012). These include, timely planting, frequent weeding (weed-free fields), ridge banking, bird scaring and timely applying of fertilisers. The aim was to mimic the subsistence farmers' cultural practices as closely as possible, but in a well-managed field.

6.2.4 Data collection

6.2.4.1 Climatic data

Daily rainfall, maximum and minimum air temperature, wind speed at 2 m from the ground surface, relative humidity, number of hours of bright sunshine, rainfall and pan evaporation data were collected on site during the experimental period. For frequency analysis, all climate data were complemented by historical records from Chitedze and KIA for Lilongwe ADD. Shire Valley ADD was complemented by data from Ngabu and Chikwawa meteorological stations. The time period of the historical records was over 30 years. The historical data was analysed for frequency and homogeneity to classify the rainfall into either dry, normal or wet year using Rainbow software (Raes et al., 2006b). Reference evapotranspiration in the two sites was estimated by FAO Penman Monteith equation (Equation 6-1) (Allen et al., 1998) through the use of ET_o calculator version 3.2 (FAO, 2012a).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma(900/(T+273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$ *Equation 6-1*

Where;

ET_o is reference evapotranspiration (mm day^{-1});
R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1});
G is the soil heat flux density (MJ m^{-2} day^{-1});
T is the air temperature at 2 m height (°C);
u_2 is the wind speed at 2 m height (m s^{-1});
e_s is the vapour pressure of the air at saturation (kPa);
e_a is the actual vapour pressure (kPa);
Δ is the slope of vapour pressure curve (kPa °C^{-1}) and
γ is the psychrometric constant (kPa °C^{-1}).

6.2.4.2 Soil data

At the start of the experiment in 2010, soil samples in the experimental plots from each site at different depths (0-0.30, 0.30-0.60 and 0.60-1.20 m) were collected. These depths does not conform to the horizons in the soil profile, rather they were used for convenience. The samples were collected from five different positions of experimental plot and analysed for soil particle distribution (percent clay, silt and sand), bulk density and organic matter (Table 6-3). The undisturbed samples, necessary for bulk density determination were sampled using kopecky rings with volume of 270 cm^3.

Table 6-3: Soil data collected during the experiments

Description	Method	Frequency
Soil texture	Pippete (Day, 1965)	Once before sowing at the start of the experiments (in 2010)
Bulk density	Undisturbed soil sampling using kopecky rings (Stolt, 1997)	Once before sowing at the start of the experiments (in 2010)
Soil water content	Gravimetric (Black, 1965)	At the start of the growing season, and every fortnight during the season
Soil pH	1:2.5; soil to water ratio (Rhoades, 1982)	Once at the start of experiments

Pedotransfer functions (Saxton and Rawls, 2006) were used to estimate volumetric soil water content at field capacity (FC), permanent wilting point (PWP), saturation point (SAT) and the saturated hydraulic conductivity (Ksat) from soil texture and organic matter data. The use of indicative values of FC, PWP, SAT and Ksat, gives good results in AquaCrop. Examples of use of pedotransfer functions in Aquacrop is presented by Shrestha et al. (2013) and Mugalavai et al. (2008) in Chitwan region (Nepal), and western Kenya, respectively.

During the growing season, soil water content in the root zone was monitored every fortnight using gravimetric method (Black, 1965). Disturbed soil samples were taken using Edelman augers (60-75 mm in diameter) at different depth intervals (0-20, 20-40, 40-60 and 60-80 cm from the ridge crest). Five randomly sampled points within the net plot were used. During each sampling, the sampled soil at each depth was mixed and a subsample for that particular depth was extracted for analysis. The pits were refilled with earth after every sampling.

6.2.4.3 Crop data

Crop phenological stages were observed throughout the growing season and cross checked with literature depending on the site and climatic conditions. For canopy cover analysis, overhead pictures were taken from each experimental plot (four pictures, i.e. one from each side of the plots) at an approximate height of 2 m from the ground at regular interval of seven days during the season. To reduce the error that can occur due to curvature of the camera lens (viewing angle), the centre square was selected as the most representative part of each picture.
The green canopy cover was determined using SigmaScan Pro software following the procedure of Karcher and Richardson (2005). The software counted the number of green pixels against the total number of pixels for each picture and present them in percentage. An average of the four pictures was used as green canopy cover percent for that particular plot. For obtaining above ground biomass yield, destructive sampling was used. Sampling was done every two weeks during the growing season. Since this is destructive, the plants were taken from a reserve area within the gross experimental plot but outside the net plot and the picture taking area. Plant samples (six plants each) from the gross plot were randomly selected, cut into small pieces and were oven dried at 60°C to constant weight. Maximum effective rooting depth was determined by digging a 1.5 m pit closer to the ridge and measuring the rooting depth after crop maturity. The profile was being washed with water to facilitate the clarity in identifying small roots at deep levels. The net plots were harvested for final yield measurement. The final yield data was recorded after sun-drying the grain until its moisture content was around 12.5%. The harvest index was calculated as the ratio of grain yield to the dry above ground biomass at harvest.

6.2.5 Data analysis

Statistical analysis was done by means of analysis of variance (ANOVA) and separation of means using GenStat 16th edition software (VSNInternational, 2013). ANOVA was used to test whether the treatments (fertilizer, and varieties) and the interaction between them have significant effect on response variables (yield and biomass). Differences between the treatment means were computed by means of the Fisher’s Least Significant Differences (LSD) at 5% level of significance.

6.3 Results and discussion

6.3.1 Climate

The collected daily rainfall data and calculated daily reference evapotranspiration during the field experiment period (October 2010-April 2013) are presented in Figures 6-1 and 6-2 for Bunda and Kasinthula respectively. The main rainy season in the study sites runs from the October until April.

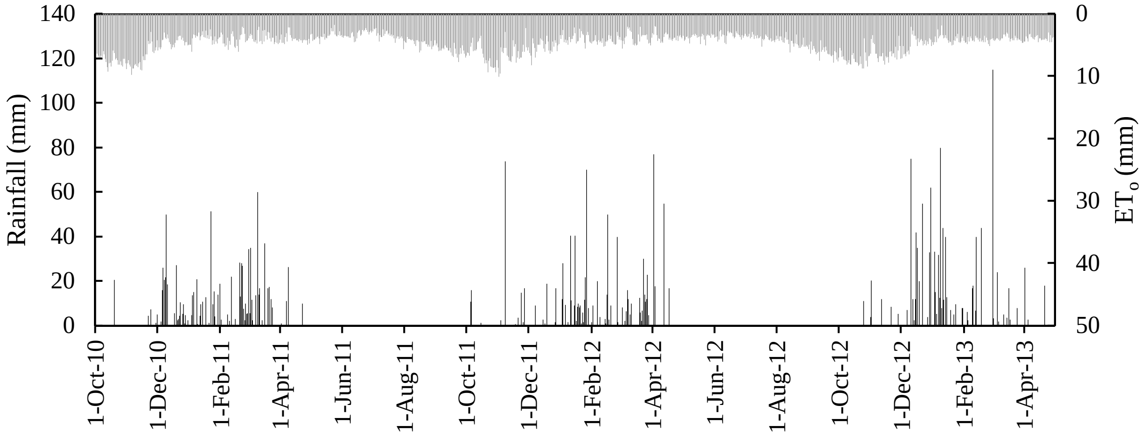

Figure 6-1: Observed daily rainfall and calculated reference evapotranspiration (ET_o) during the field experiment period for Bunda (October 2010-April 2013)

For Bunda, the 2010/11, 2011/12 and 2012/13 seasonal rainfall were 981 mm, 1010 mm and 1117 mm respectively against the historical (1980-2013) seasonal mean rainfall of 791 mm. The 20%, 50% and 80% (wet, normal and dry year) dependable rainfall for Bunda is 963 mm, 791 mm and 587 mm respectively. This means that all the field experiments were conducted in wet years at Bunda, hence water stress to crops is not expected although crop water stress is typically influenced by the rainfall distribution.

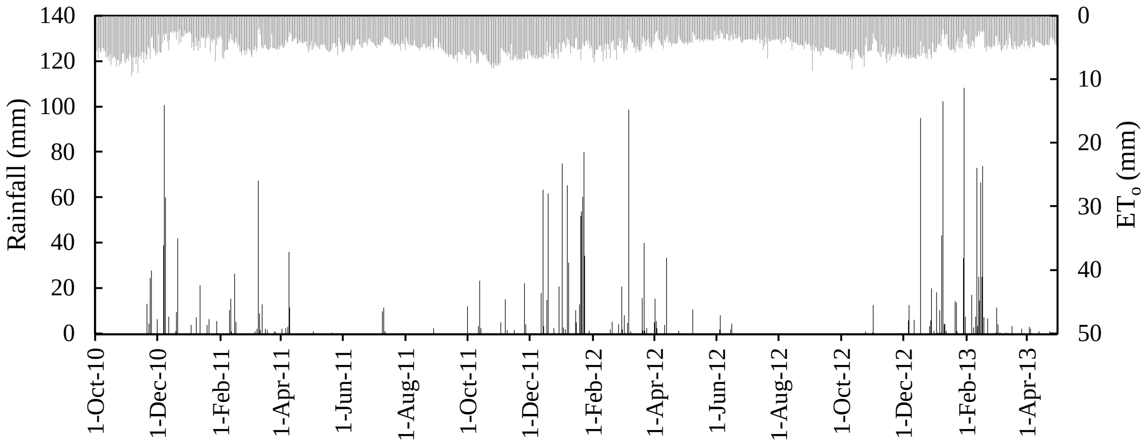

Figure 6-2: Observed daily rainfall and calculated reference evapotranspiration (ET_o) during the field experiment period for Kasinthula (October 2010-April 2013)

At Kasinthula, the 2010/11, 2011/12 and 2012/13 seasonal rainfall were 600 mm, 1029 mm, and 734 mm against a historical (1980-2013) seasonal mean rainfall of 698 mm. The dry, normal and wet year dependable rainfall are 518 mm, 698 mm and 879 mm respectively. In contrast to Bunda, Kasinthula was very wet in the 2011/12 season while 2010/11 season was a dry year. The 2012/13 season was a normal year. In both sites the reference evapotranspiration was high in summer (September, October and December) and lower in winter months of May, June and July. This is typical for most of areas in Malawi as it has a generally sub-tropical seasonal climate (Jury and Mwafulirwa, 2002).

6.3.2 Soil physical characteristics

Table 6-4 highlights the measured physical properties of the soil in the two sites. The soil texture at Bunda is classified as sandy clay with pockets of sand clay loams from the surface up to 60 cm and is generally clay deeper than 60 cm. Kasinthula has typically sandy clay loam with clay from 60 cm. The bulk density of the two sites is around 1.4 g cm^{-3}, which is good for cultivation. The organic matter contents are generally low, with Bunda having higher contents than Kasinthula. The upper layer (0-30 cm) has higher organic matter than the deeper layers, probably because of the decomposing plant materials and residual fertilizer from previous crops. These results compare well with reported values of the area by Lowole (1983) and Wiyo et al. (2000) for Bunda and Fandika et al. (2007) for Kasinthula.

Table 6-4: Soil characteristics at the experimental sites

Station	Depth (cm)	Textural class	Sand	Silt	Clay	OM	Bulk Density (g cm^{-3})
			-----------------------	%	---------------------		
Bunda	0-30	Sandy clay	48	13	39	3.29	1.46
	30-60	Sandy clay	42	13	44	2.65	1.43
	60-120	Clay	31	11	58	2.06	1.36
Kasinthula	0-30	Sandy clay loam	53	20	27	2.18	1.48
	30-60	Sandy clay loam	53	13	34	0.98	1.49
	60-120	Clay	40	20	40	0.18	1.43

Soil physical characteristics necessary for AquaCrop model which were determined using pedo-transfer functions from soil texture are presented in Table 6-5. This data is necessary for the smooth running of the model.

Table 6-5: Soil physical characteristics derived using pedo-transfer functions (Saxton and Rawls, 2006).

Station	Depth (cm)	Textural class	PWP	FC	SAT	TAW (mm m^{-1})	Ksat (mm day^{-1})
			-------------	Vol%	-----------		
Bunda	0-30	Sandy clay	24.5	36.1	45.4	116	100
	30-60	Sandy clay	27.0	38.8	46.1	118	200
	60-120	Clay	34.3	45.7	49.5	114	500
Kasinthula	0-30	Sandy clay loam	17.6	28.9	44.2	113	210
	30-60	Sandy clay loam	20	32.6	43.9	126	85.4
	60-120	Clay	24.7	37.0	46.2	123	470

PWP (soil water content at permanent wilting point); FC (soil water content at field capacity); SAT (soil water content at saturation point); TAW (total available water); Ksat (saturated hydraulic conductivity)

6.3.3 Crop yield response to different fertility levels

During the first year of the experiments (2010/11 growing season), the response of crops to different level of fertilizer application was investigated. The crops were cultivated in rainfed conditions only. The comparison of means between different treatments is shown in Tables 6-6 and 6-7 for Bunda and Kasinthula respectively.

Table 6-6: Effect of different fertilizer levels on maize and sorghum (2010/11 growing season) at Bunda.

Crop	Fertility dose	Final biomass(1) (t ha^{-1})	Final grain yield (t ha^{-1})	Calculated Harvest Index
Maize	F0	12.33_a	4.8_a	0.39_a
	F1	18.53_b	7.4_b	0.40_a
	Grand Mean	15.43	6.11	0.39
	$LSD_{0.05}$	0.66	0.62	0.04
	CV	1.2	2.9	3.1
Sorghum	F0	10.73_a	3.13_a	0.29_a
	F1	17.03_b	5.67_b	0.33_b
	Grand Mean	13.88	4.40	0.31
	$LSD_{0.05}$	0.25	1.15	0.07
	CV	0.5	7.4	6.0

F0 and F1; half and full recommended fertilizer application rate, respectively: Means with the same letters within the columns are not significantly different at α=0.05: CV; coefficient of variation and $LSD_{0.05}$; least significance difference; (1) dry above-ground biomass (grains and stover).

Table 6-7: Effect of different fertilizer levels on maize and sorghum (2010/11 growing season) at Kasinthula.

Crop	Fertility dose	Final biomass(1) (t ha^{-1})	Final grain yield (t ha^{-1})	Calculated Harvest Index
Maize	F0	9.90_a	3.54_a	0.38_a
	F1	11.17_b	4.58_b	0.35_b
	Grand Mean	10.53	4.06	0.36
	$LSD_{0.05}$	0.31	0.88	0.05
	CV	0.8	6.1	4.1
Sorghum	F0	11.83_a	4.18_a	0.35_a
	F1	12.47_b	4.95_b	0.40_b
	Grand Mean	12.15	4.56	0.38
	$LSD_{0.05}$	1.51	1.50	0.18
	CV	3.5	9.4	13.7

F0 and F1; half and full recommended fertilizer application rate, respectively: Means with the same letters within the columns are not significantly different at α=0.05: CV; coefficient of variation and $LSD_{0.05}$; least significance difference; (1) dry above-ground biomass (grains and stover).

Results show that there is significant difference in above ground biomass and yield between the F1 and F0 treatments of both maize and sorghum in the two sites. F1 has higher yields than F0. These results were expected, as application of fertilizer in Malawi has been reported to have a positive increasing effect on yield. Additional inorganic fertilizers resulted in an increase in yield in maize. According to Ikerra et al. (1999), Snapp (1998) and Wiyo (1999) maize yields increased with application of fertilizers in the fields among other management practices.

Tables 6-8 and 6-9 show results of the effect of fertilizer to biomass, yield and harvest index response of maize and sorghum in 2011/12 growing season.

Table 6-8: Effect of different fertilizer levels on maize and sorghum (2011/12 growing season) at Bunda.

Crop	Fertility dose	Final biomass[(1)] ($t\ ha^{-1}$)	Final grain yield ($t\ ha^{-1}$)	Calculated Harvest Index
Maize	F0	13.40_a	5.11_a	0.37_a
	F1	17.90_b	6.65_b	0.38_a
	Grand Mean	15.65	5.88	0.38
	$LSD_{0.05}$	1.38	1.07	0.06
	CV (%)	2.5	5.2	4.3
Sorghum	F0	10.07_a	3.42_a	0.34_a
	F1	15.07_b	5.03_b	0.33_a
	Grand Mean	12.57	4.23	0.34
	$LSD_{0.05}$	1.79	1.71	0.09
	CV(%)	4.1	11.5	7.2

F0 and F1; half and full recommended fertilizer application rate, respectively: Means with the same letters within the columns are not significantly different at α=0.05: CV; coefficient of variation and $LSD_{0.05}$; least significance difference; (1) dry above-ground biomass (grains and stover).

At Bunda, (Table 6-8), maize yields differ significantly between F1 and F0. There are also significant differences between maize biomass among the three treatments. For sorghum, yields differ significantly between F1 and F0. As already explained in section 6-1, the 2011/12 growing season was a wet year, and the effect of mid-season dry spells were not evident.

Table 6-9: Effect of different fertilizer levels on maize and sorghum (2011/12 growing season) at Kasinthula.

Crop	Fertility dose	Final biomass[(1)] ($t\ ha^{-1}$)	Final grain yield ($t\ ha^{-1}$)	Calculated Harvest Index
Maize	F0	9.66_a	3.14_a	0.33_a
	F1	12.10_b	4.47_b	0.37_b
	Grand Mean	10.88	3.81	0.35
	$LSD_{0.05}$	0.89	1.15	0.07
	CV(%)	2.3	8.6	6.0
Sorghum	F0	13.12_a	4.23_a	0.32_a
	F1	13.87_b	4.75_b	0.34_b
	Grand Mean	13.49	4.49	0.33
	$LSD_{0.05}$	0.25	0.44	0.03
	CV(%)	0.5	2.8	2.4

F0 and F1; half and full recommended fertilizer application rate, respectively: Means with the same letters within the columns are not significantly different at α=0.05: CV; coefficient of variation and $LSD_{0.05}$; least significance difference; (1) dry above-ground biomass (grains and stover).

At Kasinthula (Table 6-9), biomass, harvest index and yields of the two crops differ significantly between F1 and F0. The reason for this positive response is similar to the 2010/2011 season whereby an increase in fertilizer rate gave a positive effect on reponse variables in question (yield, biomass and harvest index). These Despite the fact that 2011/12 growing season was classified as wet year in Kasinthula, the rainfall distribution in this area is not even which is a typical characteristic of tropical climate (Vincent et al., 2013). This contributed to lower harvest than at Bunda.

In 2012/13 season, the main plots were allocated to crop cultivars and the sub-plots were the fertilizer levels. These crop cultivars were early, medium and late maturing cultivars of maize and sorghum. The results of ANOVA for these experiments are presented in Tables 6-10 and 6-11.

Table 6-10: Effect of different fertilizer levels on maize and sorghum (2012/13 growing season) at Bunda.

Crop	Cultivar/Fertilizer dose	Final biomass[1] ($t\ ha^{-1}$)		Final grain yield ($t\ ha^{-1}$)		Calculated Harvest Index	
		F0	F1	F0	F1	F0	F1
Maize	Early	12.85_a	16.47_a	4.69_a	5.96_a	0.36_a	0.36_a
	Medium	14.75_b	20.25_b	5.47_b	7.28_b	0.37_a	0.36_a
	Late	16.95_c	22.71_c	6.27_c	8.15_c	0.37_a	0.36_a
	$LSD_{0.05}$ (Cul)	2.08		0.83		0.02	
	$LSD_{0.05}$ (Fert)	1.70		0.68		0.02	
	$LSD_{0.05}$ (Cul*Fert)	2.95		1.18		0.03	
	CV(%)	9.3		10.3		4.5	
Sorghum	Early	10.12_a	15.44_a	3.08_a	5.35_a	0.30_a	0.35_a
	Medium	10.28_{ab}	16.58_b	3.13_{ab}	6.04_b	0.30_{ab}	0.36_{bc}
	Late	11.37_c	17.60_c	4.31_c	6.30_c	0.38_b	0.36_c
	$LSD_{0.05}$ (Cul)	0.74		0.57		0.02	
	$LSD_{0.05}$ (Fert)	0.60		0.47		0.02	
	$LSD_{0.05}$ (Cul*Fert)	1.04		0.81		0.03	
	CV(%)	4.2		9.5		5.1	

F0 and F1; half and full recommended fertilizer application rate, respectively: Means with the same letters within the columns are not significantly different at α=0.05: Cul; cultivar: Fert; fertility dose: CV; coefficient of variation and $LSD_{0.05}$; least significance difference; (1) dry above-ground biomass (grains and stover).

At Bunda (Table 6-10), significant differences were observed between maize cultivars under F1 treatment. The response of both crops to addition of nitrogen, resulted into higher returns in terms of biomass and yield. As expected higher yield are observed from F1 treatments. The prevailing climatic and soil conditions at Bunda were suitable for the three cultivars and hence the yield were high and closer to potential yields within this region as provided by MoAFS (2012); 4-8 $t\ ha^{-1}$ for early maturing; 5-10 $t\ ha^{-1}$ for the medium maturing and 8-15 $t\ ha^{-1}$ for the late maturing cultivar. The crop phenology of the three cultivars fitted well with the rainfall pattern of this site. No significant interactive effect between cultivars and fertilizer application rates were observed from the results.

Table 6-11: Effect of different fertilizer levels on maize and sorghum (2012/13 growing season) at Kasinthula.

Crop	Cultivar/Fertilizer dose	Final biomass[(1)] ($t\ ha^{-1}$)		Final grain yield ($t\ ha^{-1}$)		Calculated Harvest Index	
		F0	**F1**	**F0**	**F1**	**F0**	**F1**
Maize	Early	11.74_a	13.55_a	4.08_a	5.16_a	0.35_a	0.38_a
	Medium	12.41_b	13.81_b	3.74_b	3.85_b	0.30_b	0.28_b
	Late	13.34_c	13.83_b	0.97_c	1.03_c	0.07_c	0.30_c
	$LSD_{0.05}$ (Cul)	0.49		0.21		0.01	
	$LSD_{0.05}$ (Fert)	0.40		0.17		0.01	
	$LSD_{0.05}$ (Cul*Fert)	0.69		0.30		0.02	
	CV(%)	2.9		5.2		4.3	
Sorghum	Early	10.88_a	12.82_a	3.28_a	4.45_a	0.30_a	0.35_a
	Medium	10.90_a	12.77_a	3.01_b	3.41_b	0.28_b	0.27_b
	Late	11.85_b	12.82_b	2.83_c	3.08_c	0.24_c	0.24_c
	$LSD_{0.05}$ (Cul)	0.10		0.01		0.15	
	$LSD_{0.05}$ (Fert)	0.08		0.01		0.12	
	$LSD_{0.05}$ (Cul*Fert)	0.14		0.02		0.21	
	CV(%)	1.5		3.9		3.4	

F0 and F1; half and full recommended fertilizer application rate, respectively: Means with the same letters within the columns are not significantly different at α=0.05: Cul; cultivar: Fert; fertility dose: CV; coefficient of variation and $LSD_{0.05}$; least significance difference; (1) dry above-ground biomass (grains and stover).

At Kasinthula (Table 6-11), significant differences in above ground biomass, grain yield and calculated harvest indices were observed between cultivars in all treatments except biomass of F1 treatments of medium and late maturing cultivar. The observed yields of medium and late cultivars of maize fell short of the expected range of potential yields in the region as provided by MoAFS (2012); 5-10 t ha^{-1} for the medium maturing and 8-15 t ha^{-1} for the late maturing cultivar. This is attributed to the mid-season water stress which occurred later in the season and the fact that the rains stopped during flowering. Hence there was not enough conversion of biomass into grain yield. These cultivars are recommended for medium to high altitudes (Table 6-1), hence the bad performance is not surprising. The rainfall pattern at Kasinthula is usually not long (falls within a short period) hence plants with long season require supplementary irrigation to reach their full potential. The ideal cultivar for maize in this region is the early maturing cultivar. Sorghum performed well with the same effect of longer cultivars being affected by water stress later in the season. No significant interactive effect between cultivars and fertilizer application rates were observed from the results although there were significant effect of cultivars and fertilizer rates when assessed separately.

From the experiments from 2010/11 growing season through to 2012/13 growing season, the effect of increasing nitrogen is well reflected in the yields of crops. There are substantial increase of yields of both maize and sorghum in the two areas. These results are in line with what is reported by (Chirwa, 2005; Materechera and MlozaBanda, 1997; Sakala et al., 2003; Wiyo, 1999). The effect of altitude on performance of different cultivars is observed in the experiments of 2012/13 growing season. The observed yields of the cultivars were closer to the potential ranges as provided in MoAFS (2012) at Bunda than Kasinthula. This is due to the water stress that occurred at Kasinthula and failure of long cultivars to adapt to lower altitude climate. The location effect and agro-ecological effect is attributed to this performance of the crops.

6.4 Conclusion

From the results, it was observed that there is significant increase in yield of maize and sorghum with higher fertilizer application as expected. The soils responded well to fertilizer application and hence the observed response in the yields of maize and sorghum. Late maturing varieties yield more if there is adequate rainfall for the entire cropping cycle (Bunda, Fig. 6-1). However, if the late maturity cultivars are cultivated in an area with shorter rainy season (Kasinthula, Fig 6-2), they cannot mature in time before the rains stop hence the need for supplementary irrigation. Therefore it is advisable that in low altitude areas, short cultivars are suitable while in medium altitude areas, short, medium and long cultivars are suitable (Table 6-1 and 6-2).

Chapter 7
Fine-tuning and validation of AquaCrop

7.1 Introduction

A model is a simplification or abstraction of a real system (Loomis et al., 1979) while specifically a crop model is a quantitative scheme for predicting the growth, development and yield of a crop, given a set of genetic features and relevant environmental variables (Monteith, 1996). In other words, a crop model attempts to simulate the way in which a crop responds to its environment. Therefore, crop models are valuable tools to assess the impact of diverse environmental factors on crop production (Boote et al., 1996). The main objective of this chapter was to fine-tune and validate the FAO AquaCrop model for Malawian conditions. Once calibrated, the model could be applied to assess different farming strategies for farmers to improve crop yields and to assess impact of future climate change on crop yields in Malawi (Part IV).

7.1.1 Brief review of crop modelling

There are several crop models developed which can be grouped into different groups. Steduto et al. (2009) classified crop models into two main groups depending on their purpose, i.e. scientific and engineering crop models. Scientific crop models are more mechanistic and are based on the functional laws and theory of the system they model. Their main purpose is to improve knowledge and understanding of crop responses to environmental changes. Examples include DSSAT (Jones et al., 2003a), WOFOST (Boogaard et al., 1998), CropSyst (Stockle et al., 1994), EPIC (Williams et al., 1989), and APSIM (Holzworth et al., 2014; Keating et al., 2003). The models require relatively complicated and extensive number of input parameters that are not easily available for a diverse range of crops. Engineering models on the other hand are a mixture of well-established theory and robust empirical relationships and their purpose is to provide predictions and advice for management decision making (Passioura, 1996; Steduto et al., 2009). The major drawback of these models is that they tend to be static during model runs. They are not dynamic, in adjusting parameters if a stress occurs during model runs. These stresses could be water, temperature, salinity and fertility stress. A more dynamic approach in the engineering-type models would be needed if using crop models for reliable decision making in crop management and predictions of crop production. With AquaCrop, FAO aims at bridging this gap.

In this research the multi-crop water productivity model developed by FAO, AquaCrop (Raes et al., 2009; Steduto et al., 2009; Vanuytrecht et al., 2014a), was selected not only because of its novelty and wide application but also the dynamic approach it uses in crop development and maintenance of reasonable accuracy with simple and robust procedures. The AquaCrop model has been applied in several regions of the world and has performed satisfactory. For instance, with less inputs, AquaCrop simulated both biomass and yield similar to crop models CropSyst and WOFOST which differ in complexity, number of inputs and driving mechanisms for growth simulation (Todorovic et al., 2009).

AquaCrop has some limitations, including as pointed out by Vanuytrecht (2013) the omission of the direct impact of solar radiation on crop production (in terms of day length, radiation level) which may have an impact on crop simulations in high latitude, and the potential loss of detail due to simplification of physiological processes. Despite of these limitations, the characteristics of the environment where this research was conducted, requires crop models like AquaCrop if crop modelling research is to be successfully carried out.

7.1.2 FAO AquaCrop Model

AquaCrop is a multi-crop water productivity model. It was developed by FAO to help project managers, consultants, irrigation engineers, agronomists, and even farm managers with the formulation of guidelines to increase the crop water productivity for both rainfed and irrigated production systems for diverse locations and seasons (Raes et al., 2009; Steduto et al., 2009). The calculation scheme of AquaCrop model is presented in figure 7-1.

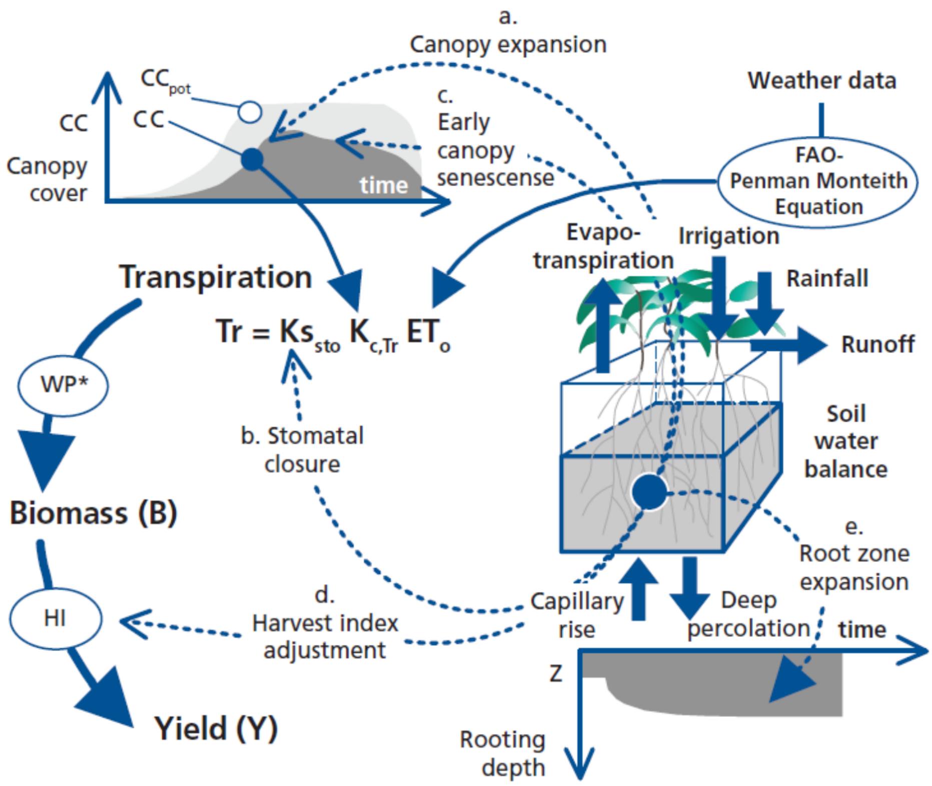

Figure 7-1: Schematic representation of calculation scheme of AquaCrop with indication (dotted arrows) of the process (a to e) affected by water stress. CC is simulated canopy cover, CC_{pot} the potential canopy cover, Ks_{sto} the water stress for stomatal closure, $K_{c,tr}$ the crop transpiration coefficient (determined by CC and $K_{c,trx}$), ET_o the reference evapotranspiration, WP the normalized water productivity for ET_o and air CO_2 concentration and HI the harvest index (Raes et al., 2009; Steduto et al., 2012)*

AquaCrop simulates crop development and production under a range of environmental and management conditions. These are based on user-specified inputs of daily climatic data (rainfall, minimum and maximum temperature and reference evapotranspiration (ET_0)), soil physical characteristics (total available soil water content and saturated hydraulic conductivity), crop characteristics (crop phenology for the local cropping environment), irrigation and field management information. It uses a relatively small number of explicit parameters and largely intuitive input variables (Raes et al., 2009) and pursues an optimum balance between simplicity, accuracy and robustness (Steduto et al., 2009).

AquaCrop simulates crop yield (Y) based on the amount of water transpired by the crop (Tr), in the absence of soil fertility stress during crop production. This is expressed by Equation 7-1;

in which transpiration depends on climatic conditions (reference evapotranspiration) and the green canopy cover (CC), through the crop transpiration coefficient (KC_{Tr}).

$$Tr_i = Ks_i \times KC_{Tr_i} \times ETo_i \qquad \textit{Equation 7-1}$$

Where;

Tr_i is the crop transpiration (mm day^{-1}) on day i;
ETo_i is the reference evapotranspiration (mm day^{-1}) and;
KC_{Tr_i} is the crop transpiration coefficient (dimensionless);
Ks_i is the soil water stress coefficient (dimensionless).

Instead of leaf area index, AquaCrop uses canopy cover to describe crop growth. The expansion of CC from its initial value (CC_0) to reach the maximum (CC_x), is described by a logistic function determined by the canopy growth coefficient (CGC). At the end of the growing season, the decline of the CC due to senescence is described by means of the canopy decline coefficient (CDC). Transpiration is converted into dry above-ground biomass (B) by means of the normalized crop water productivity (WP*). This process is presented by Equation 7-2.

$$B = Ks_{b_i} \times WP^* \times \sum_{i=1}^{n} \frac{Tr_i}{ETo_i} \qquad \textit{Equation 7-2}$$

Where;

B is the cumulative above-ground biomass production (g m^{-2});
WP^* is the normalized crop water productivity (g m^{-2});
n is the sequential days spanning the period when biomass is produced;
Ks_{b_i} is the cold stress coefficient for biomass production (dimensionless).

Crop yield in AquaCrop is determined based on biomass. It is computed as the product of the final biomass multiplied by harvest index (*HI*) as presented in Equation 7-3.

$$Y = B \times HI \qquad \textit{Equation 7-3}$$

Where;

Y is the dry mass yield production (g m^{-2});
B is the cumulative above-ground biomass production (g m^{-2}) and;
HI is the harvest index.

Instead of using a nutrient balance, AquaCrop uses a semi-quantitative assessment to determine the degree of stress that a crop experiences from nutrient deficiencies (Van Gaelen et al., 2014). This semi-quantitative measure corresponds to the maximum relative dry above-ground biomass (B_{rel}) that can be expected in a fertility stressed environment with reference to stress-free conditions. This is presented in Equation 7-4. B_{rel} ranges from 0%, corresponding to complete crop failure from nutrient deficiency, to 100%, indicating no nutrient stress.

$$B_{rel} = \frac{B_{stress}}{B_{ref}} \times 100\% \qquad \textit{Equation 7-4}$$

Where;

B_{rel} is the maximum relative dry above-ground biomass (%);
B_{stress} is the total dry above-ground biomass at the end of the growing season in a field with soil fertility stress (g m^{-2}) and;

B_{ref} is the total dry aboveground biomass at the end of the growing season in a field without soil fertility stress (g m^{-2}).

Both B_{stress} and B_{ref} are to be recorded in well-watered fields (no soil water stress) and free of any other stress factors, such as weeds, pests, diseases and salinity. Being a semi-quantitative input parameter, B_{rel} can be obtained easily. B_{stress} is the maximum biomass that can be produced under the governing local conditions in a field that is only affected by soil fertility stress (the soil fertility stressed field) in a good rainy year, or under irrigation when there is no water stress. The biomass is then expressed as a percentage of the biomass produced under stress-free conditions (B_{ref}), which can be obtained from experimental fields or from published potential yields. In addition, model simulations can provide an estimation of the biomass for the local farming conditions under stress-free conditions (the reference field).

AquaCrop determines the soil water content in the root zone (SWC) by means of a soil water balance that keeps track of incoming (rainfall, irrigation and capillary rise) and outgoing (runoff, deep percolation and evapotranspiration) daily water fluxes. A maximum of five soil horizons, each with its own specific soil physical characteristics, can be incorporated into the model (Raes et al., 2012). When the soil water content in the root zone drops below conservative thresholds, which are process and crop-specific, soil water stress will affect root zone expansion, canopy expansion and early senescence, transpiration and the harvest index. The relative intensity of the water stress on the various target model parameters is determined by the relevant stress coefficients (Ks), which vary between 1 (no stress) and 0 (full stress) and are related to the soil water content by a concave stress curve. Further description of concepts of the AquaCrop model calculation procedure and algorithms are described in more detailed in (Raes et al., 2009).

Canopy development is affected by a series of stresses in which AquaCrop demonstrates though stress coefficients (Ks). Ks are indicators of relative intensity of the effect (water, temperature, salinity or fertility), in essence, Ks is a modifier of its target model parameter which varies in value from 1, when the effect is non-existent, to 0 when the effect is maximum (Raes et al., 2012). Water, temperature, salinity or fertility stress may limit canopy expansion resulting in less crop transpiration.

Soil water, soil fertility and soil salinity stress decrease canopy expansion. As a result, the expected CC_x might not be achieved or achieved much later in the season. The adjustment on canopy expansion is simulated by multiplying the target model parameter CGC with the corresponding stress coefficient (Ks < 1). Under severe water stress, the canopy development might be brought to a standstill and canopy senescence might even be triggered. Also when the crop transpiration is fully inhibited CC no longer can increase. Soil fertility and soil salinity stress do not only decrease the growing capacity of the crop but affect as well the maximum canopy that can be reached (CC_x) and result in a steady decline of the canopy cover once CC_x is reached at mid-season (Raes et al., 2012).

Before a crop model can be applied in a particular region, it should be calibrated and validated for the environment of interest if results are to be credible (Xiong et al., 2008). Model calibration involves minimizing the error between model outputs and observed data and the determination of model parameters for an intended purpose while model validation assesses the ability of a calibrated model to simulate the characteristics of an independent dataset (Carbone et al., 2003; Irmak et al., 2005; Jones et al., 2003a). To achieve satisfactory simulations, merely fine-tuning of local specific parameters may be sufficient, but in cases where the fine-tuned model does not give desired performance, additional calibration of conservative parameters is necessary (Vanuytrecht, 2013). To this end a sensitivity analysis is necessary to determine which parameters should be prioritized during an efficient calibration process.

7.2 Materials and methods

7.2.1 Data collection

Data for the fine tuning and validation of the model were obtained from the field experiments at Bunda and Kasinthula as described in Chapter 6. The parameters observed included canopy cover (CC), soil water content (SWC), maximum effective rooting depth (Z_r), aboveground biomass (B) and grain yield (Y). Daily weather data (rainfall, maximum and minimum temperature, air humidity, direct sunshine hours and wind run) were observed on site.

7.2.2 Fine-tuning and calibration

Experimental data from the 2010/11 growing season was used for fine-tuning the model. The full recommended fertilizer application rate treatments (F1) were used for fine-tuning the model while the half recommended fertilizer application rate treatments (F0) were used for soil fertility stress calibration. Model validation used data from the 2011/12 and 2012/13 growing seasons.

AquaCrop provides a set of crop parameters for different crops as default values in two major categories, conservative and non-conservative parameters:

- Conservative crop parameters are assumed to be constant and generally applicable to a wide range of environmental conditions and usually crop specific. Generally, they require no modifications from the default values provided by AquaCrop.
- Non-conservative crop parameters are usually cultivar specific and are specific to local conditions. These parameters are defined by the user as input or calibrated/fine-tuned before the model can be applied to a new environment as recommended by Hsiao et al. (2009). These parameters are limited, measurable and physiologically meaningful. Examples of these parameters include the length of growing period and plant phenological stages, planting density, sowing date, initial and maximum canopy cover, maximum rooting depth and reference harvest index. Fine tuning these parameters ensures correct application of the model to a specific environment.

The non-conservative crop physiological parameters, except crop responses to fertility, were adjusted according to field data obtained in the 2010/11 cropping season for both maize and sorghum with F1 treatments at the two sites. On-site climatic data and measured initial soil water content for the 2010/11 growing season were used.

The guidelines for model calibration/fine tuning of Steduto et al. (2012) whereby the common procedure of trial and error iteration is encouraged, were followed. The procedure assesses specific output variables (CC, SWC, B throughout the season, and final B, Y and total ET at crop maturity) as the reference variables in the calibration and recommend adjusting only those non-conservative parameters that are known to influence the reference variable the most. These parameters include plant density, length of growing period, initial and maximum CC, canopy decline, maximum rooting depth, soil moisture content at field capacity (FC), and permanent wilting point (PWP) and harvest index. Fine tuning was stopped when simulations matched well with measured data.

7.2.2.1 Calibration of crop responses to soil fertility

Mineral nutrient stress, particularly nitrogen stress can reduce canopy expansion resulting in a slower canopy development which in turn reduces maximum canopy cover (CC_x) that a crop can attain resulting in less dense canopy (Raes et al., 2009). In addition, the water productivity (WP*) is reduced if the crop is exposed to long term nutrient (nitrogen) stress. However, AquaCrop does not simulate nutrient cycles and nutritional effects on the crop directly (Steduto et al., 2012). Rather, it describes crop response to soil fertility stress by a qualitative assessment, which is based on fundamental concepts (Raes et al., 2012; Van Gaelen et al., 2014). Crop response to soil fertility stress is described with non-conservative parameters which requires calibration for each specific case.

Table 7-1: Stress coefficient used for simulation of crop response to soil fertility stress and the target crop parameter. (Source; Raes et al. (2012))

Coefficient	Description	Target crop parameter
$Ks_{exp,f}$	Stress coefficient for canopy expansion	Canopy Growth Coefficient (CGC)
Ks_{CCx}	Stress coefficient for maximum canopy cover	Maximum canopy cover
$f_{CDecline}$	Stress decline coefficient of the canopy cover	Canopy Cover (CC) once maximum canopy cover has been reached
Ks_{WP}	Stress coefficient for biomass water productivity	Biomass water productivity (WP*)

Soil fertility calibration in AquaCrop requires field observations from optimal fertility trials without water stress. In this study, these data were not available as all the treatments were rainfed, the common practice by majority of farmers in the area. In this research, the plots with F1 treatments were considered as ‘reference field’ and F0 as ‘stressed field’. Since the 2010/2011 season was considered wet, it was assumed that the crops did not suffer significant water stress. The process of calibrating soil fertility was done by inputting the following field observed data into AquaCrop;

- The ratio between the biomass observed in the stressed field (F0) and the biomass observed in the reference field (F1);
- The observed maximum canopy cover (CC_x) at stressed field;
- The class of the canopy cover decline during the season once CC_x is reached.

AquaCrop uses these three inputs, to select values for the four stress coefficients ($Ks_{exp,f}$, Ks_{CCx}; $f_{CDecline}$ and Ks_{WP} (Table 7-1)) automatically by means of an iterative optimization algorithm.

7.2.3 Validation

Validation of the fine-tuned model was done by using data collected from the 2011/2012 and 2012/2013 growing season in both sites. The procedure was to run the model with necessary input data for these growing seasons, and compare the simulations with field observations.

7.2.4 Evaluation of model results

Evaluation of model performance is important to provide a quantitative estimate of the ability of the model to reproduce observable variable (Krause et al., 2005). Several statistical indicators, each with own strengths and weaknesses, are available to evaluate the performance of a model. Therefore having an ensemble of different indicators is necessary to sufficiently assess the performance of the model. The fit between the observed and simulated SWC, CC, B and Y was assessed by a combination of graphical displays (plots of simulated versus observed values) and three statistical indicators. These statistical indicators are relative root mean square error (Loague and Green, 1991), squared Pearson's correlation coefficient (Draper and Smith, 1998) and Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970).

7.2.4.1 Pearson correlation coefficient (r^2)

The Pearson correlation coefficient (r^2) gives the amount of variance explained by the model compared to the total observed variance. It ranges from 0 to 1, with higher values expressing a better linear relationship between the observed and predicted relative yield:

$$r^2 = \left(\frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}}\right)^2$$

Equation 7-5

Where;

O_i are observed values;
P_i are predicted values;
$\bar{O}$ is the mean of the observed values;
$\bar{P}$ is the mean of the predicted values and;
n is the number of observations.

7.2.4.2 Relative Root Mean Square Error (RRMSE)

RRMSE is expressed as a percentage and gives an indication of the relative difference between predicted and observed data (Jacovides and Kontoyiannis, 1995). According to Jamieson et al. (1991), a simulation can be considered excellent if RRMSE is smaller than 10%, good if between 10 and 20%, fair if between 20 and 30% and poor if larger than 30%.

$$RRMSE = \frac{1}{\bar{O}}\sqrt{\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{n}}100$$

Equation 7-6

Where;

O_i are observed values;
P_i are predicted values;
$\bar{O}$ is the mean of the observed values and;
n is the number of observations.

7.2.4.3 Nash-Sutcliffe model efficiency coefficient (EF)

The Nash-Sutcliffe model efficiency coefficient (EF) determines the relative magnitude of the residual variance compared to the variance of the observations (Nash and Sutcliffe, 1970). It indicates the robustness of the model and ranges from minus infinity to 1. An EF of 1 indicates a perfect match between the model predictions and observations, an EF of 0 means that the model predictions are as accurate as the average of the observed data and a negative EF occurs when the mean of the observations is a better prediction than the model.

$$EF = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2 - \sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$ *Equation 7-7*

Where;

O_i are observed values;
P_i are predicted values;
$\bar{O}$ is the mean of the observed values and;
n is the number of observations.

7.3 Results and discussion

7.3.1 Fine-tuning and calibration of crops in the two sites

The crop and soil data collected as described in section 6.2.4 from experimental plot F1 were used to fine-tune the crop parameters. The crop parameters which were altered from the default values during the fine-tuning process are presented in Table7-2.

Table 7-2: Conservative (Raes et al., 2012) and non-conservative parameters fine-tuned to the local environments

	AquaCrop default		Bunda		Kasinthula	
	Maize	**sorghum**	**Maize**	**sorghum**	**Maize**	**sorghum**
A. Conservative crop parameters						
Base temperature (°C)	8	8	8	8	8	8
Upper temperature (°C)	30	30	30	30	30	30
Crop coefficient when canopy is complete but prior to senescence	1.05	1.07	1.05	1.08	1.05	1.1
Water productivity normalized for ET_o and CO_2 (gram m^{-2})	33.7	33.7	33.7	30	32.0	32
Possible increase (%) of HI due to water stress before flowering	0	4	0	0	0	10
Coefficient describing positive impact of restricted vegetative growth during yield formation on HI	7	1	7	1	7	1
Coefficient describing negative impact of stomatal closure during yield formation on HI	3	3	3	3	3	3
Allowable maximum increase (%) of specified HI	15	25	15	25	15	25
Soil water depletion factor for canopy expansion – Upper threshold	0.14	0.15	0.14	0.15	0.14	0.15
Soil water depletion factor for canopy expansion – Lower threshold	0.72	0.7	0.72	0.7	0.72	0.7
Soil water depletion fraction for stomatal control – Upper threshold	0.69	0.7	0.69	0.7	0.69	0.7
Soil water depletion factor for canopy senescence – Upper threshold	0.69	0.7	0.69	0.7	0.69	0.7
Minimum growing degrees required for full biomass production (°C-day)	15	12	15	12	15	12
B. Fine-tuned non-conservative parameters						
Plant density (no. of plants per hectare)	75000	200000	54000	106667	54000	106667
Emergency (days after sowing)	6	11	5	6	6	6
Senescence (days after sowing)	107	132	87	100	80	96
Maturity (days after sowing)	132	147	100	115	104	115
Maximum canopy cover (%)	96	99	75	80	75	75
Flowering (days after sowing)	66	87	56	70	46	50
Maximum effective rooting depth (m)	2.3	1.8	0.6	0.6	0.8	0.7
Reference harvest index (%)	48	45	40	35	38	35

The effects of soil fertility in the calibration fields for maize and sorghum were fine-tuned with data presented in Table 7-3.

Table 7-3: Data used for calibrating soil fertility stress for sorghum and maize

Site	Crop	Relative biomass production (%)	Reduction in maximum CC (%)	Reduction in canopy expansion (%)	Average canopy cover decline (%/day)	Reduction in biomass water productivity at end of season (%)
Bunda	Maize	69	10	7	0.10	47
	Sorghum	63	22	3	0.10	51
Kasinthula	Maize	74	13	7	0.10	36
	Sorghum	81	15	2	0.01	25

After fine-tuning the model, simulations of CC, B, SWC and Y were evaluated. The observed and simulated CC for maize and sorghum for the two sites is presented in Figure 7-2.

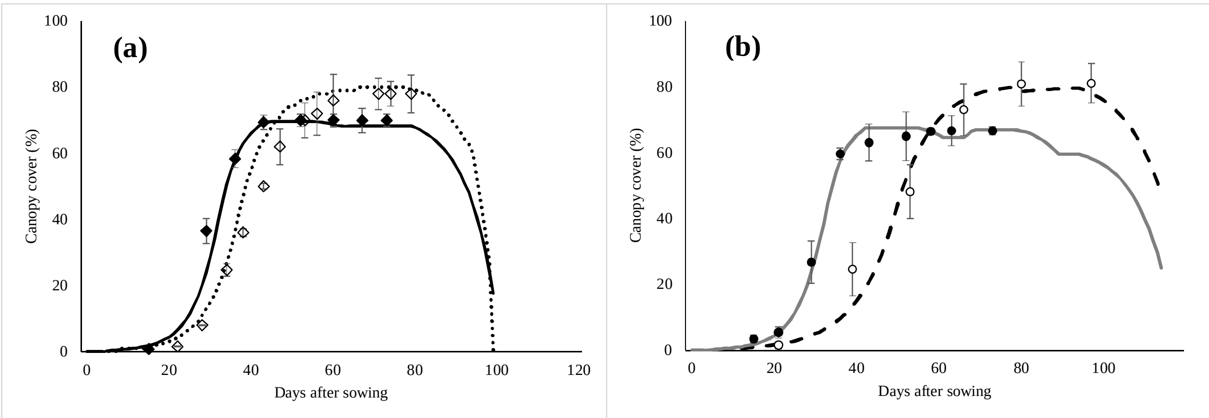

Figure 7-2: Canopy cover evolution during the 2010/11 growing season: (a) Maize: Simulated (lines): dotted (Bunda), solid (Kasinthula). Observed (diamonds): open (Bunda), solid (Kasinthula) with error bars indicating ±standard deviation: (b) Sorghum: Simulated (lines): dashed (Bunda), grey (Kasinthula). Observed (circles): open (Bunda), solid (Kasinthula) with error bars indicating ±standard deviation.

The CC development followed the standard logistic growth curve used by AquaCrop for non-stressed conditions (Raes et al., 2012). The simulated and observed CC fitted well during the season. For maize, in Bunda CC_x (80%) was higher than in Kasinthula (70%). For Kasinthula, there was a good match between observations and simulated values, unlike for Bunda where between 40 to 60 days after sowing (DAS), there was an overestimation by the model. Kasinthula maize reaches CC_x quicker than Bunda maize. This is due to different climatic conditions and exposure to sunlight. During the growing season, Kasinthula is warmer than Bunda, hence has high radiation which in turn results in fast growth of the crop. Just like maize, sorghum CC_x at Bunda was higher (80%) than at Kasinthula (70%) and slower crop growth was observed. The simulated CC at Kasinthula reflected the water stress which occurred during the season from 60 DAS, resulting in a reduction in CC. This water stress is clearly displayed in the SWC graph of the root zone (Figure 7-4b). The observations show that different cereals respond differently to environmental conditions and stresses.

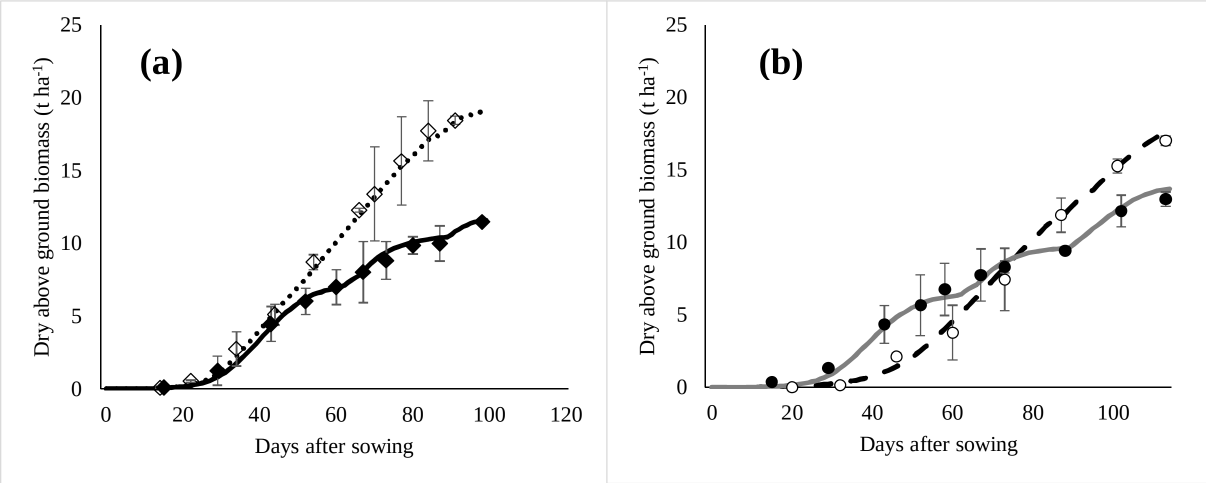

Figure 7-3: Above-ground biomass accumulation during the 2010/11 growing season: (a) Maize; Simulated (lines) dotted (Bunda) solid (Kasinthula). Observed (diamonds) open (Bunda) solid (Kasinthula) with error bars as ±standard deviation: (b) Sorghum; Simulated (lines) dashed (Bunda) grey (Kasinthula). Observed (circles) open (Bunda) solid (Kasinthula) with error bars as ±standard deviation.

As expected from CC, the biomass (B) of maize at Bunda was higher than at Kasinthula as presented in Figure 7-3. This might be due to the effect of soil nutrient levels (inhibition due to soil chemical characteristics) in the two sites. The soil characteristics at Bunda are more fertile compared to Kasinthula. This resulted in lower yields in Kasinthula than in Bunda (Figure 7-5). The simulations matched well with the observations as confirmed by statistical indicators in Table 7-4. For sorghum, analogous results as for maize are observed. Following the lower CC, sorghum at Kasinthula had lower B than at Bunda. The model simulated B accumulation of the crops well in the two sites.

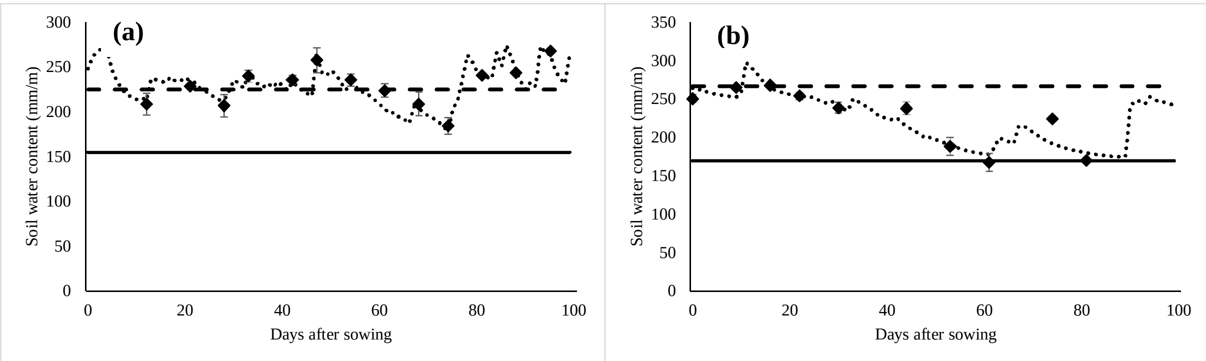

Figure 7-4: Root zone soil water content evolution for the 2010/11 growing season for maize (a) Bunda; (b) Kasinthula. Simulated (dotted lines) and observations (symbols). Error bars indicate ± standard deviation. Horizontal lines indicate the soil water content at field capacity (dashed line) and at permanent wilting point (solid line).

The observed and simulated SWC for maize for the 2010/11 growing season from the two sites is presented in Figure 7-4. AquaCrop simulated well the evolution of SWC in both sites. At Bunda the SWC was always around field capacity (FC) while in Kasinthula the water content was below FC but above permanent wilting point (PWP). This might explain the poor performance of the crops at Kasinthula. There was water stress which might have induced early canopy senescence and hence low yield.

The final simulated grain yield was finally compared with the observed final grain yield collected for different soil fertility levels. The simulated yield fitted well with the observed yield (Figure 7-5). The statistical indicators (Table 7-4) confirm that the model was calibrated well for the two sites.

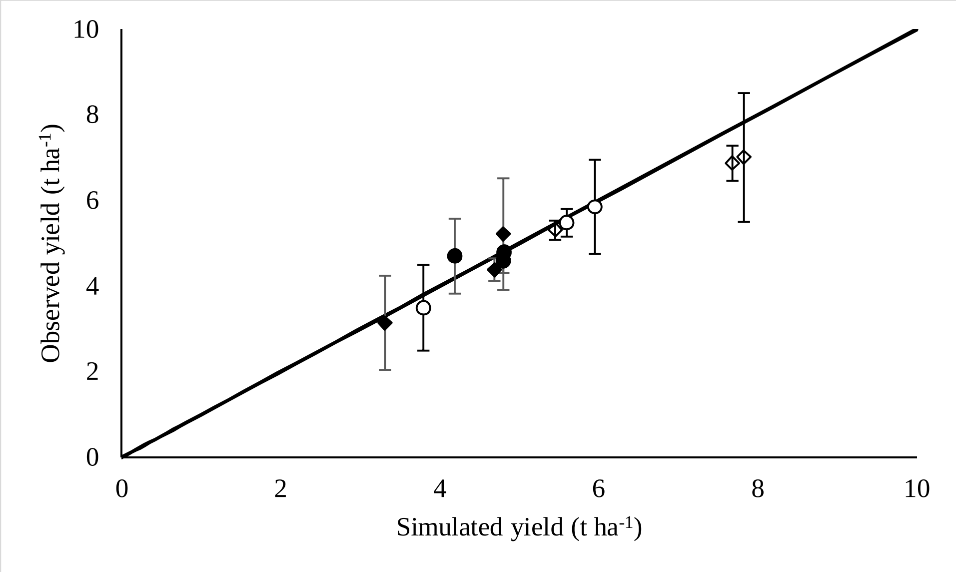

Figure 7-5: 1:1 plot comparing observed yield with simulated yield for maize (diamonds) and sorghum (dots) at Bunda (open) and Kasinthula (solid) for calibration (2010/11 growing season).

From Figure 7-2 through to 7-5, it can be seen that there was a good match between observations and simulated values in CC, B, SWC and Y.

After fine-tuning the crop parameters, the model performed well in both sites, confirmed by the statistical indicators (Table 7-4). The r^2 was high for B, SWC, CC and Y in the two sites with values over 90%. The model performed excellent in simulating B, SWC, CC and Y with RRMSE values less 10% except for maize biomass at Bunda and sorghum biomass at Kasinthula which were just above 10%. Nevertheless, this indicates that the model fine-tuning was excellent (Jamieson et al., 1991). As for EF, the model performed well in all parameters under test. B, SWC, CC and Y were close to 1. Based on these results, the model was deemed to have been accurately fine-tuned to the sites for both maize and sorghum.

Table 7-4: Statistical evaluation results for model calibration

			Statistic			
Site	**Crop**	**Parameter**	**n**	**r^2**	**RRMSE (%)**	**EF**
Bunda	Maize	CC	6	0.99	5.7	0.98
		Biomass	10	1	10.3	0.98
		SWC	13	0.91	3.2	0.89
		Y	3	0.89	6.9	0.86
	Sorghum	CC	6	1	6.3	0.99
		Biomass	10	0.99	8.2	0.99
		SWC	13	0.90	3.4	0.88
		Y	3	0.92	7.5	0.85
Kasinthula	Maize	CC	9	0.99	6.0	0.98
		Biomass	10	0.99	7.2	0.98
		SWC	10	0.85	6.2	0.85
		Y	3	0.87	7.9	0.82
	Sorghum	CC	9	0.99	6.8	0.99
		Biomass	10	0.97	11.5	0.97
		SWC	10	0.91	6.5	0.88
		Y	3	0.90	8.0	0.80

7.3.2 Validation of the fine-tuned model

Validation was done using independent data from the 2011/12 and 2012/13 growing seasons. AquaCrop was able to predict CC for both maize and sorghum (Figure 7-7). An example of CC evolution within a growing season (2011/12) is presented in Figure 7-6. Maize CC_x at Bunda was higher than at Kasinthula. However for sorghum, CC_x was similar in the two sites but there was a more rapid canopy evolution in Kasinthula compared to Bunda. This might be attributed to quick growing tendency of chosen cultivars in Kasinthula because of its climatic characteristics. Kasinthula is hot and on lower altitude, and usually receives low rainfall. Figure 7-7 shows a good match between observed and simulated canopy cover on a 1:1 plot confirming a good fine-tuned model which can be used for further scenario analysis.

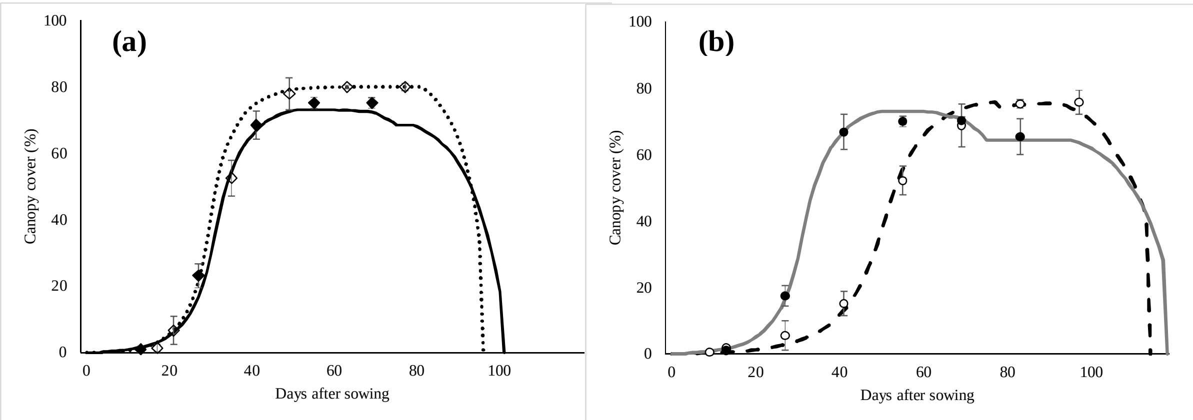

Figure 7-6: Canopy cover evolution during the 2011/12 growing season: (a) Maize; Simulated (lines) dotted (Bunda) solid (Kasinthula). Observed (diamonds) open (Bunda) solid (Kasinthula) with error bars as standard deviation: (b) Sorghum; Simulated (lines) dashed (Bunda) grey (Kasinthula). Observed (circles) open (Bunda) solid (Kasinthula) with error bars as ± standard deviation.

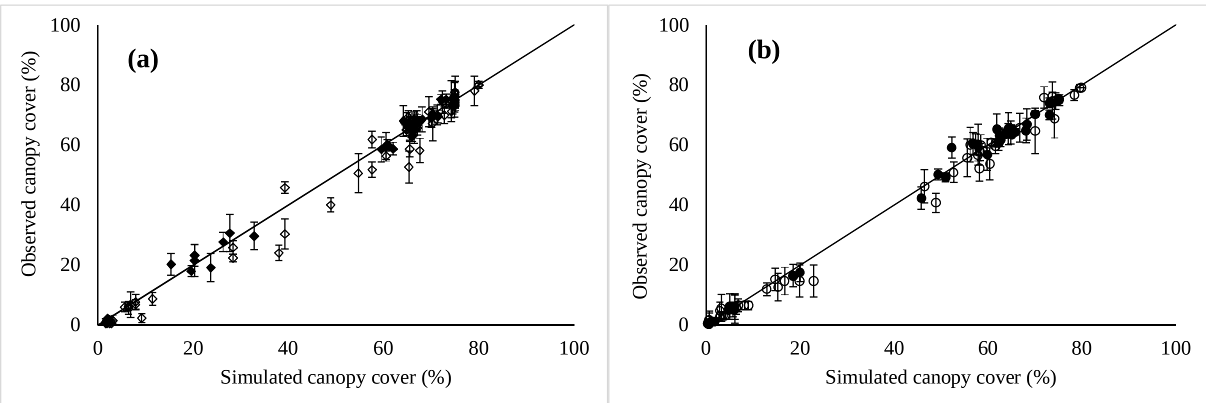

Figure 7-7: Regression between observed and simulated canopy cover: (a) Maize; symbols (open) Bunda (solid) Kasinthula, with error bars as ±standard deviation; (b) Sorghum; symbols (open) Bunda (solid) Kasinthula, with error bars as ±standard deviation.

Just like CC, AquaCrop simulated the above-ground biomass of the two crops well in the two sites. Model simulations match well with field observations (Figure 7-9). An example for the 2011/12 season shows that Bunda has higher biomass than Kasinthula, which is attributed partly to climatic differences and partly to management practices in the two areas. Bunda is wetter and had good rains in the two years in contrast with Kasinthula (Figure 7-8).

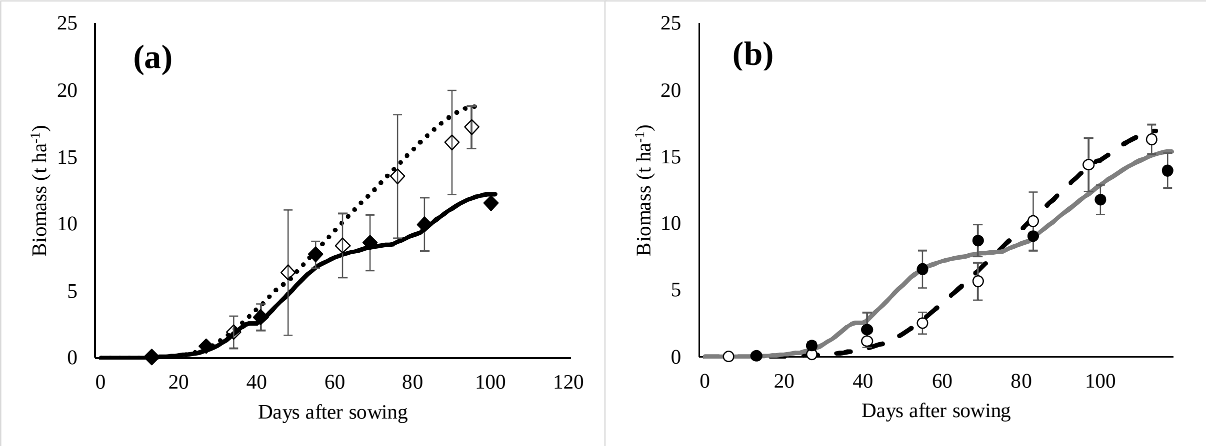

Figure 7-8: Above-ground biomass accumulation during the 2011/12 growing season: (a) Maize; Simulated (lines) dotted (Bunda) solid (Kasinthula). Observed (diamonds) open (Bunda) solid (Kasinthula) with error bars as standard deviation: (b) Sorghum; Simulated (lines) dashed (Bunda) grey (Kasinthula). Observed (circles) open (Bunda) solid (Kasinthula) with error bars as ± standard deviation.

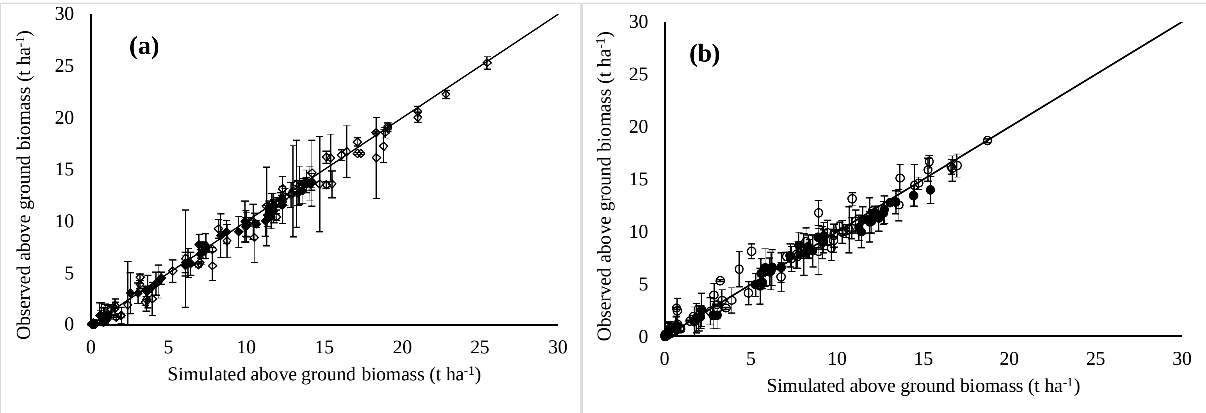

Figure 7-9: Regression between observed and simulated above ground biomass: (a) Maize; symbols (open) Bunda (solid) Kasinthula, with error bars as ±standard deviation; (b) Sorghum; symbols (open) Bunda (solid) Kasinthula, with error bars as ±standard deviation.

Observed soil water content in the root zone was used to confirm the correct simulation of crop transpiration which is governed by the fine-tuned canopy development, climatic conditions (rainfall and ET_o) and water stress. Generally, there was a good match between observed and simulated soil water content as shown in Figure 7-11, for the two sites. A site analysis example is presented for 2011/12 season in Figure 7-10. In Kasinthula, there was a mid-season water stress which is clearly reflected after 50 DAS. The SWC steadily approached PWP at Kasinthula while it was around FC at Bunda. The soil water fluxes within the season are well predicted by the model.

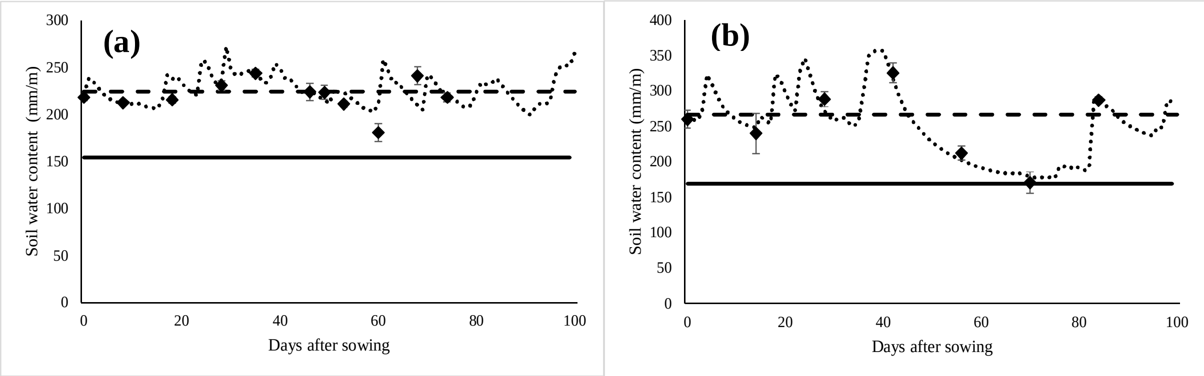

Figure 7-10: Root zone soil water content evolution for the 2011/12 growing season of maize (a) Bunda; (b) Kasinthula. Simulated (dotted lines) and observations (symbols). Error bars indicate ± standard deviation. Horizontal lines indicate the soil water content at field capacity (dashed line) and at permanent wilting point (solid line).

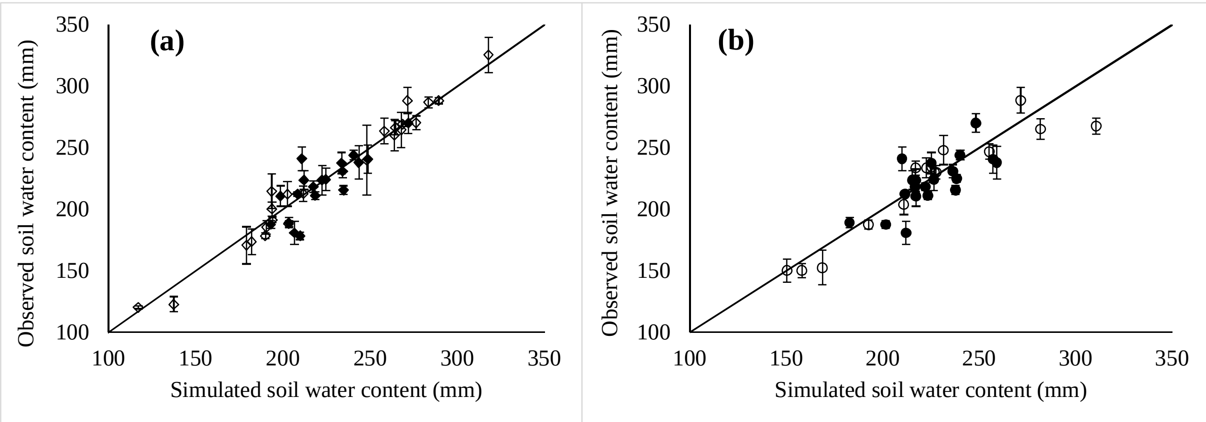

Figure 7-11: 1:1 plot comparing observed and simulated root zone water content for (a) maize fields (diamonds) and (b)sorghum fields (dots); open symbols (Bunda) and solid symbols (Kasinthula).

The comparison between simulated grain yield and observed yields of the 2011/12 growing season gave a good match (Figure 7-12). There is a good match of observed and simulated yields in the two areas. The data points are close to the 1:1 line, confirming that the model can predict yields well.

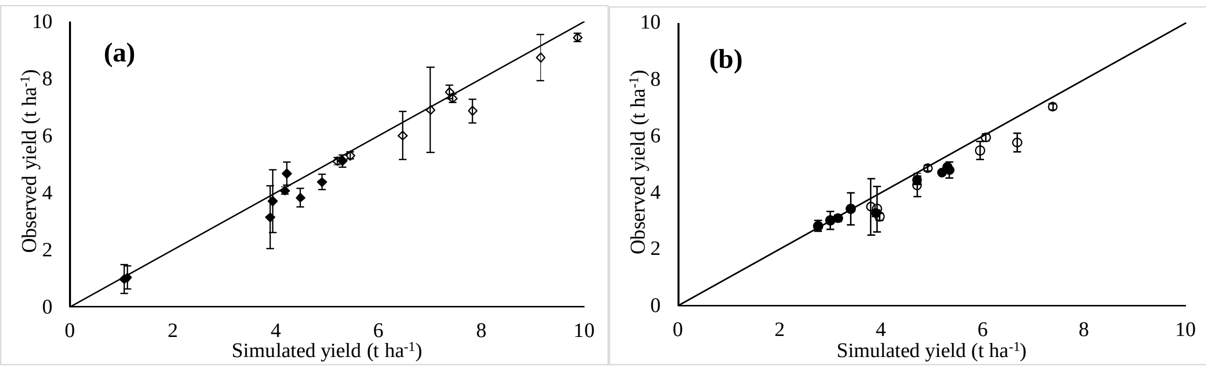

Figure 7-12:1:1 plot comparing observed and simulated yield for (a) maize (diamonds) and (b)sorghum (dots); open symbols (Bunda) and solid symbols (Kasinthula).

The statistical evaluation of the model indicated good fit between observations and simulated outputs (Table 7-5). The results are deemed adequate indicating the ability of AquaCrop to simulate maize and sorghum in the two sites.

Table 7-5: Statistical evaluation results for model validation (2011/12 and 2012/13 growing seasons).

			Statistic			
Site	**Crop**	**Parameter**	**n**	**r^2**	**RRMSE (%)**	**EF**
Bunda	Maize	CC	74	0.99	6.9	0.98
		Biomass	80	0.96	9.5	0.98
		SWC	20	0.94	7.3	0.64
		Y	9	0.99	5.9	0.91
	Sorghum	CC	74	0.99	7.3	0.99
		Biomass	80	0.98	14.6	0.97
		SWC	20	0.99	6.7	0.39
		Y	9	0.99	10.8	0.83
Kasinthula	Maize	CC	44	0.99	3.9	0.99
		Biomass	64	0.99	5.7	0.99
		SWC	20	0.99	3.9	0.97
		Y	9	0.99	12.2	0.91
	Sorghum	CC	44	0.99	4.3	0.96
		Biomass	64	0.93	9.7	0.98
		SWC	20	0.91	7.1	0.99
		Y	9	0.99	9.7	0.79

For yield, the model predicted well with what was observed on the field. However the values seem to be higher than what is reported by the government services (~1-2 t ha^{-1}). This difference is attributed to different management practices. The yields reported in this research are from on station, fully controlled field with timely management and adequate inputs applied. The government reports estimated regional yields from local farmer's fields which are usually not well managed and cultivated with limited inputs. The soil water contents in the two sites were well simulated hence the model can be used for formulation of different strategies as well as yield prediction in the two sites.

7.4 Conclusion

AquaCrop was successfully calibrated and validated for maize and sorghum for two sites in Malawi, i.e. Bunda and Kasinthula. The model can be used for formulating and evaluating different strategies and their effects to yield and crop production. In this research, the model will now be used to evaluate the effect of future climate change on yield in Malawi.

Part IV Simulation and Assessment

Chapter 8
Simulation of historical yields

8.1 Introduction

In this chapter the yield stability for maize and sorghum, under rainfed-conditions, and over the growing seasons, are assessed by means of the calibrated AquaCrop model. For the two study sites (Bunda and Kasinthula) simulations were run, not only for the two fertility levels (F1 and F0) considered in the field experiments, but also for the fertility level as observed in farmers' fields (FM). Another objective of this chapter is to check if AquaCrop can accurately simulate past yields before being used to project future crop production (Chapter 9).

8.2 Materials and methods

The validated AquaCrop model for maize and sorghum (as outlined in Chapter 7) in two sites were used to simulate historical crop yields. Model inputs required for this chapter were obtained from historical records as presented in Table 8-1.

Table 8-1: Description of historical data used in running AquaCrop for Bunda and Kasinthula

Input	Description	Bunda	Kasinthula
Climate	Rainfall, Max and min temperature ET_o $[CO_2]$	43 years (1970-2013)	33 years (1980-2013)
Soil	Observed soil texture in the study area	Sandy Clay (TAW = ~ 120 mm m^{-1})	Sandy Clay loam (TAW = ~ 110 mm m^{-1})
Crop	Maize	Early maturing cultivars (100 days)	Early maturing cultivars (100 days)
	Sorghum	Intermediate maturing cultivars (115 days)	Intermediate maturing cultivars (115 days)
Field management (Soil fertility)	As considered in field experiments (Chapter 6)	F1 (recommended fertilizer dose), F0 (half recommended fertilizer dose)	F1, F0
	Estimated from historical production records	FM (Farmers practice)	FM
Irrigation management	Rainfed	F1, F0, FM	F1, F0, FM
	Net irrigation requirement	F1	F1

8.2.1 Climate

Historical daily rainfall records, maximum and minimum temperature and estimated evapotranspiration (ET_o) from temperature data were used as climatic inputs for the two sites. ET_o was calculated according to the FAO Penman-Monteith equation (Allen et al., 1998). $[CO_2]$ was set equal to the measured $[CO_2]$ at the Mauna Loa observatory in Hawaii in each of the years of the 1970-2013 time period (Figure 8-1).

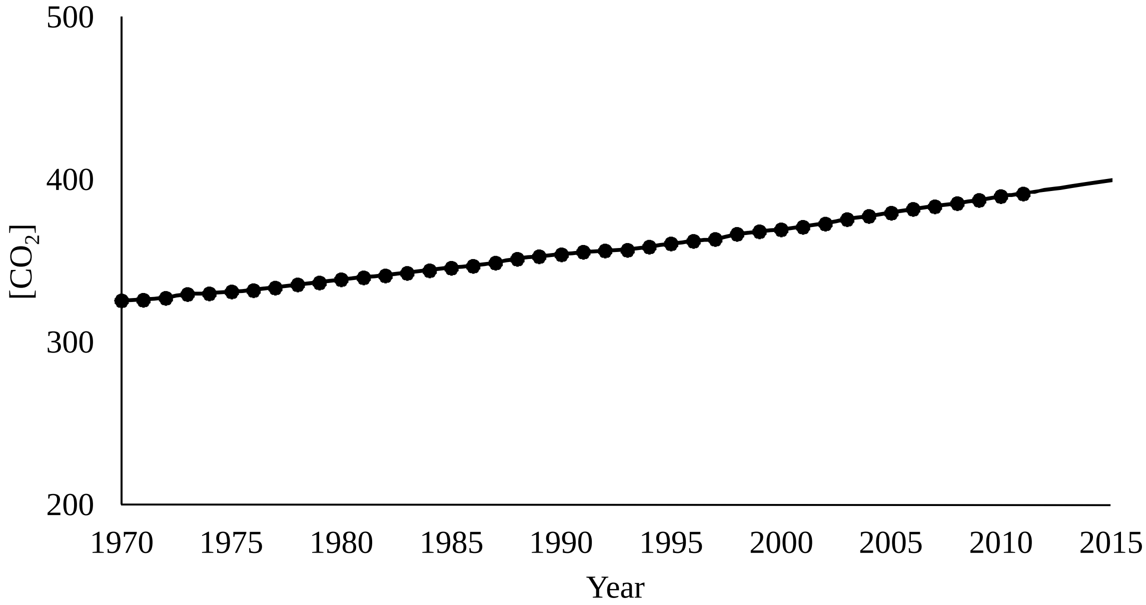

Figure 8-1: Average atmospheric CO_2 concentration as observed in Mauna Loa observatory (Hawaii, USA)

8.2.2 Soil

The observed soil types in the sites were used. The physical characteristics of these soils are presented in Chapter 6. To take into account the effect of physical characteristics on crop yields in the study area, the soils were classified according to the estimated amount of total available water (TAW) classes which is 120 mm m^{-1} group. This is the average TAW for the soil textural classes of the two sites. Since the water table in the two sites was very deep (>5 m) capillary rise was not considered.

8.2.3 Crop

Crop parameters for maize and sorghum already calibrated in Chapter 7, were used in this analysis. The maize cultivar used was an early maturing (100 days) while the sorghum cultivar was intermediate maturing (115 days). The onset dates of the growing season were generated based on rainfall, as planting for rainfed agriculture is typically determined by rainfall events (Raes et al., 2012).
The second occurrence (starting from 1 October) of a rainfall sum of 30 mm in five days was selected as the onset date. This mimics the farmer’s strategy:

- The second occurrence is selected, since farmers want to be assured that the rainfall season has really started;
- The 30 mm in five days is sufficient to wet the top soil (0.3 m) in which the seeds are planted.

The search window for the onset dates was from 1 October to 31 January. In case the criteria are not met, farmers are very likely not plant, so there were no simulation runs for that season. The particular season was considered a failure year. That said, planting does not guarantee that the year is not a failure year, since long dry spells in the growing season might result in early canopy senescence and no yield.

8.2.4 Management

8.2.4.1 Field management

The field management practices used in calibration for the two sites were used. That is the relative biomass (B_{rel}) for F1 (unlimited; recommended fertilizer dose) and F0 (limited soil fertility; half of recommended fertilizer dose) treatments were used.

Additionally, B_{rel} obtained with common farmer field management practices (FM) was considered. This was done because even with F0 the model simulated higher yields than what is reported in government reports. B_{rel} was estimated from the long term mean yields of the crops in Lilongwe ADD and Shire Valley ADD as reported in Malawi government reports (MoAFS, 2012). B_{rel} for FM was calculated by taking the proportion of historical observed yield over simulated non-stressed yield. B_{rel} of FM was 40%, which corresponds to a 60% soil fertility stress. This lower value takes into account the effect of farmer’s management, i.e. a much lower fertilizer application rate than recommended by the government.

The field surface practices in both sites were set so that no runoff occurred as the crops were grown on ridges with no soil bunds and no surface mulches.

8.2.4.2 Irrigation

To check the potential yield that would have been obtained in case the crops were cultivated under no water stressed conditions, simulations for irrigated agriculture were done. Net irrigation water requirements (Inet) were determined by setting the threshold below which the depletion in the root zone may not drop at the upper threshold for leaf expansion stress. This guarantees a fully developed canopy cover and the absence of stomatal closure. Irrigation simulations were only run with unlimited soil fertility (F1) to simulate the maximum potential yield expected in a non-stressed field.

8.2.5 Initial conditions

All simulations were run from 1 October for each growing season until crop maturity. Since the simulations were starting at the end of the long dry season (1 October), the initial soil water content for the whole soil profile was set to wilting point, which mimics realistic field conditions. The model was run successively for 43 and 33 growing seasons for Bunda and Kasinthula, respectively, corresponding to the available input climatic data (Table 8-1).

8.3 Evaluation

Simulated mean yields were compared with the reported regional farmers' yields and among each other for different field management practices. Distinction was made between failure years (no yield) and non-failure years. The stability of crop yield across years as a response to field management was assessed using the coefficient of variation (CV), which measures the extent of variability of yields to the mean;

$$CV = \frac{\sigma}{\mu} \times 100\% \qquad \textit{Equation 8-1}$$

Where;

CV is the coefficient of variation (%);

σ is the standard deviation and;
μ is the mean

8.4 Results

8.4.1 Evaluation of historical crop yield as a response to management strategy

Table 8-2 shows the number of failure years and their percentage of occurrence for both sites. Lower CV values for non-failure (rainfed) yields only than for failure and non-failure yields altogether were noted. This indicates an artificially higher stability if failure years are not considered. It was also observed that there is a high risk in rainfed farming as portrayed by the high standard deviations and CV values for yield when all years of simulation runs are analysed. This is due to several reasons among which the greatest is climate variability and effects of El Niño in the area. During some El Niño years, there are long drought spells hence no yield is expected. Kasinthula is more affected by these climatic events as confirmed by the higher number of failure years than Bunda.

Table 8-2: Number of failure years (rainfed agriculture) for Bunda and Kasinthula

Site	Number of failure years	% of occurrence
Kasinthula	7	21
Bunda	3	7

Table 8-3 shows simulated historical crop yields for different field management strategies. The results shows that rainfed yields from F1 are higher than for F0 and FM as expected. This is a result of high nutrient levels from full fertilizer application dose. This shows that applying less fertilizer results in lower but more stable yields. The expected yields under full irrigation are very high. This is because the simulations for irrigation ensured that the crops did not suffer any water or fertility stress. Inter annual variation of the yields is due to CO_2 fertilization, and the variation of the length of growing cycle (as a result of temperature differences between the years), which is very low compared to the variability due to water stress.

Table 8-3: Simulated historical mean yields for different management practices. Failure years are presented as percentage of the ratio of number of failure years to total number of years used

Site	Crop	Management	Years used	Mean ($t\ ha^{-1}$)	Standard deviation	CV (%)
Kasinthula	Maize	F1	All	4.005	2.52	63
			Non-failure only	5.084	1.55	31
		F0	All	3.289	1.94	59
			Non-failure only	4.174	0.98	23
		FM	All	1.864	1.01	54
			Non-failure only	2.365	0.28	12
		Irrigation	All	6.950	0.21	3
	Sorghum	F1	All	4.047	2.92	72
			Non-failure only	4.947	2.43	49
		F0	All	3.548	2.45	69
			Non-failure only	4.336	1.96	45
		FM	All	1.976	1.11	56
			Non-failure only	2.415	0.65	27
		Irrigation	All	5.537	0.25	3
Bunda	Maize	F1	All	6.801	2.05	30
			Non-failure only	7.311	0.83	11
		F0	All	4.881	1.40	29
			Non-failure only	5.247	0.37	7
		FM	All	2.498	1.12	45
			Non-failure only	2.984	0.11	4
		Irrigation	All	8.105	0.22	3
	Sorghum	F1	All	4.959	1.79	36
			Non-failure only	5.331	1.18	22
		F0	All	3.315	1.04	31
			Non-failure only	3.564	0.51	14
		FM	All	2.045	0.78	38
			Non-failure only	2.314	0.21	9
		Irrigation	All	6.092	0.27	5

Table 8-4 shows the simulated length of growing cycle and net irrigation requirement (Inet) for maize and sorghum in Kasinthula and Bunda. The mean length of growing cycle is longer in Bunda than in Kasinthula for the two crops. This is explained by the different climatic characteristics of the two areas. Because of higher temperature in Kasinthula, the crops accumulate the required number of growing degrees to reach maturity faster than in Bunda. Kasinthula has higher Inet than Bunda (Table 8-4). The fact that the two areas are in different agro-ecological zones, explains the difference in crop water and irrigation water requirements. Kasinthula, being at a lower altitude, has a hot and dry climate with high atmospheric demand hence high evapotranspiration and associated crop water requirements. Lower rainfall in Kasinthula increased Inet further.

Table 8-4: Simulated length of growing cycle and net irrigation requirement (Inet)

Site	Crop		Mean	Standard deviation	CV (%)
Kasinthula	Maize	Cycle (days)	92	3	3
		Inet (mm)	226	91	40
	Sorghum	Cycle (days)	105	8	8
		Inet (mm)	282	100	35
Bunda	Maize	Cycle (days)	96	3	3
		Inet (mm)	91	39	43
	Sorghum	Cycle (days)	113	5	4
		Inet (mm)	116	48	41

The stability of the yields using different fertility management were assessed and the results are presented in Figures 8-2 and 8-3.

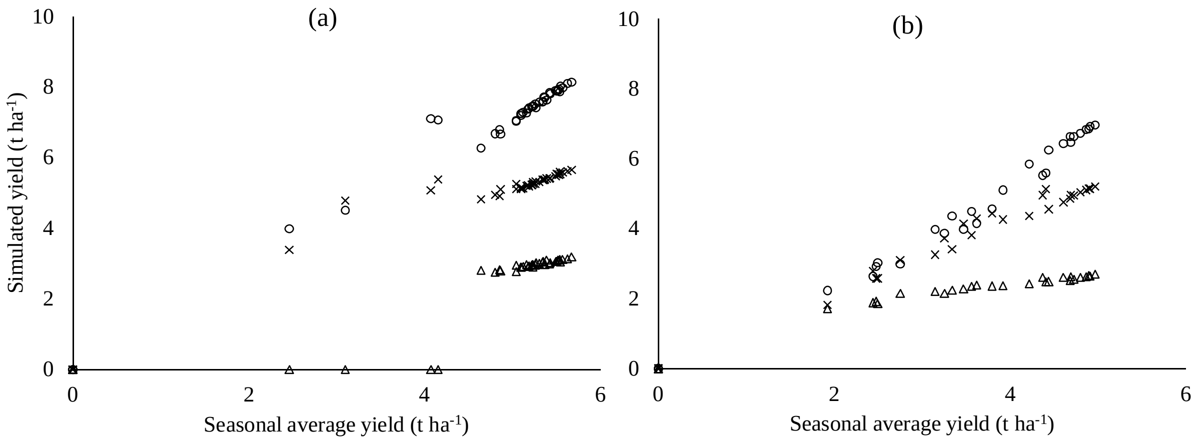

Figure 8-2: Stability analysis of maize yields; (a) Bunda (b) Kasinthula. The circles represents F1, crosses F0 and triangles FM

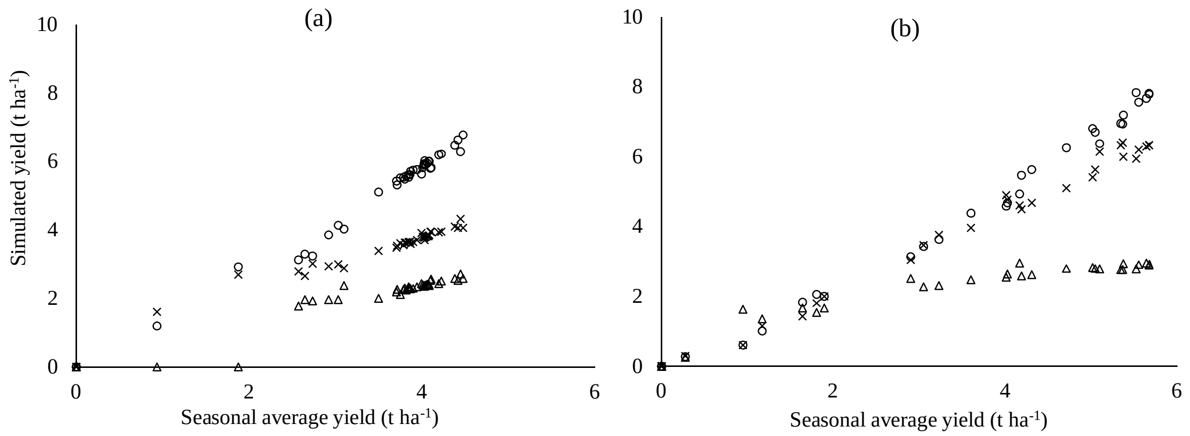

Figure 8-3: Stability analysis of sorghum yields; (a) Bunda (b) Kasinthula. The circles represents F1, crosses F0 and triangles FM

FM strategies have a narrow range of simulated yields compared to both F1 and F0 for both maize and sorghum in the two sites. This shows that FM strategy is more stable as evidenced by the range of simulated yields over the seasons. The F1 and F0 management strategies offers a wide range which indicates instability of the yields. The slope of the points for these two (F1 and F0) management strategies is steeper with F1being more steep and wide than F0. The FM strategy is horizontal in Kasinthula compared to Bunda. This means that if farmers continue what they practice now, they are assured of having yields. This calls for a cautious approach to adoption of the other strategies as they are not that stable and if rainfall is a problem. In good rainy years, F1 and F0 have high yields but none or very little in bad rainy years unlike FM where the yields are fluctuating around 2 t ha^{-1}. Even though this yield is on the lower side, but the fact that it is stable (its range is small), it is still a preferably good management.

8.5 Conclusions

Crop yields under farmers' soil fertility strategy (FM) are in the range of 1.9 to 3.0 ton ha^{-1} for maize and 2.0 to 2.3 ton ha^{-1} for sorghum. They are a bit higher than what is reported by the government studies (1-2 ton ha^{-1}), but this is due to the absence of the effect of the simulations of pests, diseases and weed infestation in the current version of AquaCrop. Additionally runoff was not considered in the simulation.

With full soil fertility (F1) the production can be easily doubled, but this will simultaneously increase the yield variability. This means that very good yields can be expected in good rainy years, but that the crop yield will be lower than under FM strategies in drier years. Given the limited resources of the households, farmers are not likely to change their soil fertility management.

The occurrence of failure years is relatively high with almost 1 year out of 10 in Bunda and 2 years out of 10 in Kasinthula. Contrary to what can be expected from the rainfall analysis in Chapter 4, the average yield in the period 1995-2009 did not drop below the yield for the period 1980-1994. It even increased slightly.

Chapter 9
Assessing the effect of climate change on cereal production

9.1 Introduction

There has been a lot of research on effects of climate change on agriculture in the southern Africa region in recent years. The studies focused on various aspects and impacts of climate change including rainfall and increased carbon dioxide levels (Cooper et al., 2008; Hewitson and Crane, 2006; Usman and Reason, 2004). The IPCC fourth assessment report suggests that the temperature for the whole of Africa will increase more than the global temperature by the end of this century (IPCC, 2007). Other studies project that by 2100 there will be a reduction in maize production in southern Africa under possible increase of El Niño-Southern Oscillation (ENSO) conditions (Stige et al., 2006). Droughts, which are strongly associated with ENSO are expected to become more frequent and intense under a changing climate (Hewitson and Crane, 2006). It is predicted that yields for staple cereals will fall sharply with a 1-2 °C change in temperature and more erratic rainfall patterns (Cane et al., 1994; Stige et al., 2006). This poses a major risk for the subsistence agriculture sector, which is the main source of livelihood for the majority of the population in this region (Osgood et al., 2008). It is worth noting that most of these studies have been either very broad or overlooked the importance of considering the worst affected clientele in this cycle, which is the smallholder farmer. Our research instead zooms in on the main agricultural production regions of Malawi, and takes into account the field management practices by smallholder farmers in simulation of the effect of climate change on crop yields.

Most farmers in sub-Saharan Africa, as in Malawi, rely on rainfed agriculture (Baron et al., 2005; Wiyo et al., 2000). These are smallholder farmers characterized by low-income levels, marginalised living conditions and reliance on monocropping. They are most likely to be worst affected by climate change. At present, the farmers are facing problems of insufficient food production which can be linked to the varying and changing climate (Chapter 8). Other issues including expensive farm inputs, small land holdings because of population pressure, lack of knowledge to adapt the variable climate in their farming calendar hinder them from maximizing their crop productivity potential (see Chapter 3).

In recent years, higher rainfall variability is observed compared to the previous decades (IPCC, 2007). This has shortened the season suitable for crop growing and implies that dry spells occur frequently (see Chapter 4). For the future, with the projected increase in climatic changes, rainfall variability will be exacerbated (see Chapter 5). Thus, there will be higher risk to have low crop production. Similarly, the greenhouse gases have their effect on the global air temperature, which is evidenced by increasing temperatures (IPCC, 2007). This in turn affects evaporation and crop transpiration on the fields which will lead to low soil water content, ultimately low crop production. On the other hand, higher atmospheric CO_2 concentration has a positive effect on the biomass water productivity (WP*) which results in higher yield in the absence of stresses (CO_2 fertilisation) (e.g. Vanuytrecht et al. (2012)). The total effect of increased rainfall variability and climatic changes on crop yield can be estimated with crop water productivity models such as AquaCrop.

The main objective of this chapter is to assess the effects of future climate change on maize and sorghum yields in Malawi by means of AquaCrop. AquaCrop is able to simulate future yields as it is already shown that it can simulate yield range due to water stress and fertility ranges (Section 7.1.2) and the integration of results in AquaCrop from assessment of the effect of elevated [CO_2] on key macro-scale growth processes, parameters and variables of agricultural crops as observed in FACE experiments by Vanuytrecht et al. (2012). In this research, the assessment is done for the mid-21st century, the 2050s through the use of IPCC SRES scenarios A1B. By considering the results from Chapter 8, an evaluation of the simulated crop yield of the baseline is worked out.

9.2 Materials and methods

The assessment of the effects of climate change on maize and sorghum was done for Chitedze station (Section 5.2.1.1) owing to its complete climatic daily records for a long period. Data used for this part is broadly categorised into four main sections as in Table 9-1.

Table 9-1: Description of data used for simulating future yields with AquaCrop

Input	Description	Comment
Climate	Rainfall Max and min temperature ETo [CO_2]	Climate change factors from 15 CMIP3 GCMs (SRES A1B) for 2050s downscaled by LARS-WG..
Soil	TAW classes	3 soil classes (80, 120 and 160 mm m^{-1})
Crop	Maize and Sorghum	3 (early, intermediate and late maturing) cultivars per crop (maize; 100, 120, 140 days: sorghum; 90, 115, 120 days)
Management practices	Field experiments and estimated from historical production records	F1(recommended doses), F0 and FM

9.2.1 Climate

The future climate dataset generated by the LARS-WG as described in Chapter 5 was used as weather input in AquaCrop. One dataset for the baseline period (1970-2013) and 15 datasets of A1B emission scenarios for the future were used. Each dataset consisted of 100 years which were not cumulative in time but one by one representative for the whole period. The number of years was chosen to ensure long simulation series for adequate risk assessment. ET_o was estimated from temperature data using the FAO Penman-Monteith equation (Allen et al., 1998). [CO_2] was set equal to 369.41 ppm for the baseline period. This is the average observed level of [CO_2] at the Mauna Loa Observatory between 1970 and 2013 (Figure 8-1). [CO_2] for the future climate was assumed to be 532 ppm. This is the projected [CO_2] level for 2050 for A1B emission scenarios (IPCC, 2007).

9.2.2 Soil

Three soil types which were categorised in classes of total available water content were used in the simulation, i.e. 80, 120 and 160 mm m^{-1} TAW, representing loamy sand, sandy clay loam and loam soil textures, respectively. These represent common soil texture types in central Malawi. The soil profiles were assumed to be deep and without restrictive layers. Shrestha (2014) demonstrated that running simulations for soils with different TAW values can capture the heterogeneity of the soil physical characteristics in a region.

The different soil fertility levels (F1, F0 and FM) on the other hand capture the heterogeneity of the soil chemical characteristics and field management in the region.

9.2.3 Crop

Crop information as described in Section 8.2.3 was used. Additional cultivars were used for future simulation. Early, intermediate and late cultivars for both maize and sorghum were used. The maize cultivars were 100, 120 and 140 days for early, intermediate and late maturing cultivars respectively. Sorghum had 90, 115 and 120 days for early, intermediate and late maturing cultivars respectively. Only the non-conservative parameters in the crop files were adjusted from the validated crop files (Chapter 7). Just like the historical simulations, the same criterion was used to generate onset dates of the growing season based on rainfall. In the case where this criterion was not met, that particular season was taken as a failure year. That said, planting does not guarantee that the year is not a failure year, since long dry spells in the growing season might result in early canopy senescence and no yield.

9.2.4 Management

Management practices described in Section 8.2.4 were used. This is for both field management and irrigation.

9.2.5 Initial conditions

All simulation were run from 1 October for each growing season until crop maturity. The simulations were starting at the end of long dry season, hence initial soil water content for the whole soil profile was set to wilting point.

Each scenario (16 in total; 1 baseline and 15 future) was run successively for 99 growing seasons (which stretch over two calendar years) implying 1584 runs per unique crop, soil class, cultivar and field management combination. Three cultivars (early, intermediate and late maturing); three soil classes (TAW = 80, 120 and 160 mm m^{-1}); and three management practices (F1, F0 and FM) were evaluated in this scenario analysis. This results in 42,768 theoretical combinations. In reality less model simulations were performed since some combinations were not realistic (e.g. low TAW and late maturing cultivar). The schematic flow diagram of the whole process is shown in Figure 9-1.

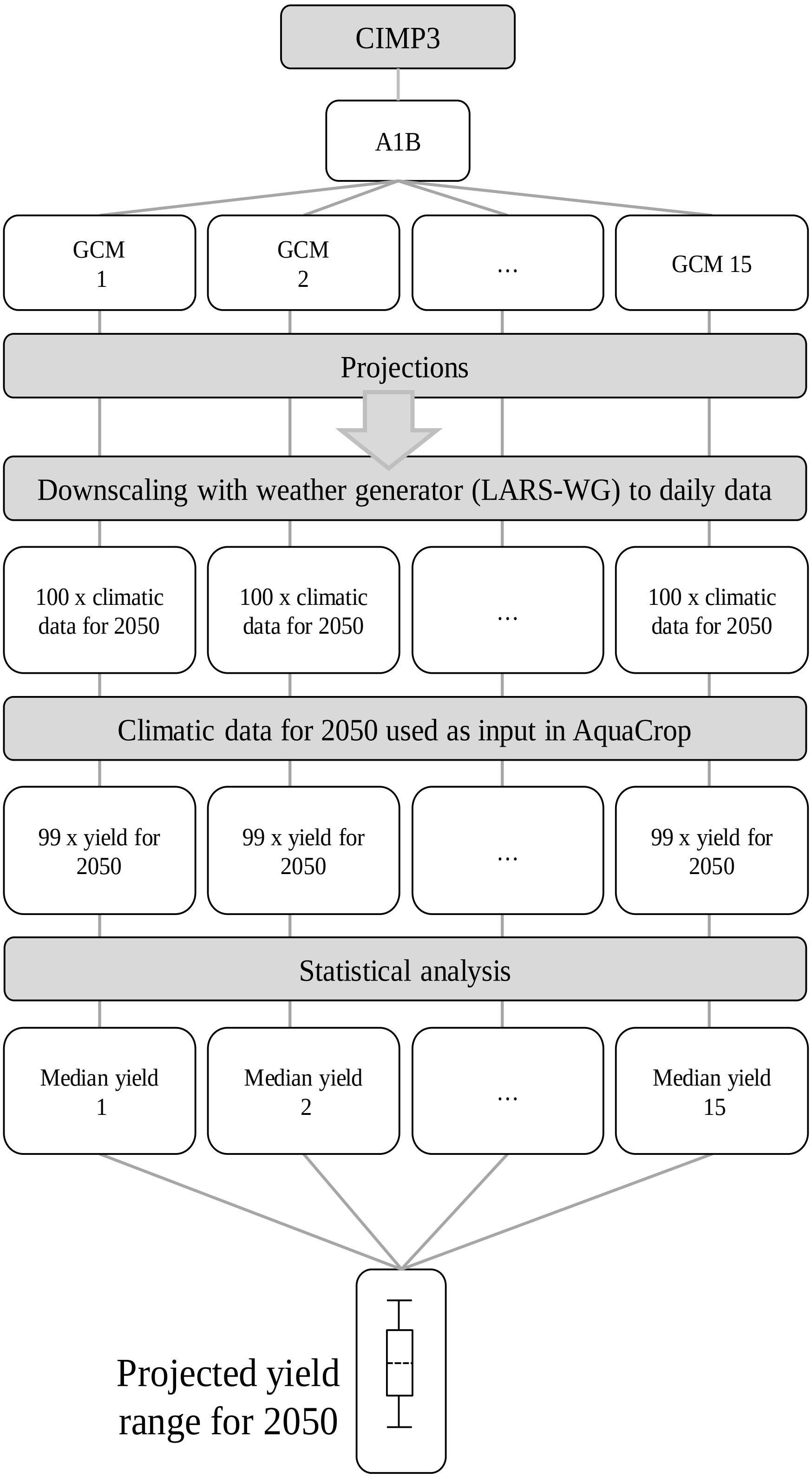

Figure 9-1: Schematic presentation of impact assessment methodology from climate data generation to calculation of predicted impacts.CMIP3 is the Coupled Model Intercomparison Project Phase3 ensemble of global climate models (GCMs); adapted from Vanuytrecht (2013).

9.3 Validation of generated weather data

Generated historical weather data were already validated by statistical correspondence of the distributions of generated and observed weather variables (See Chapte5). In this chapter, also the statistical characteristics of the distributions of simulated yield and length of growing cycle under observed and generated weather data.
Non-parametric two-sample Kolmogorov-Smirnov (KS) test for probability distribution comparison and un-paired t-tests for comparison of means were used. These tests were applied to compare the observed versus baseline simulated yields and length of growing cycle. The null hypothesis of equal distributions (KS-tests) and equal means (t-tests) were tested at the threshold of $p < 0.05$ and $p < 0.01$ to identify significant effects.

9.4 Impact evaluation

The impact of projected climatic changes on crop production was assessed by studying the final crop yield, and length of growing cycle. Projected crop yields were computed for each of the GCMs and grouped into one boxplot for evaluation against the median baseline yield, both for maize and sorghum. Coefficient of variability of final yield, crop growing cycle and Inet was calculated to assess the variability of the production using Equation 8-1.

9.5 Results

9.5.1 Validation of generated weather data

The KS-and t-tests results obtained from comparing the outputs of AquaCrop from using inputs of observed (Chapter 8) versus generated baseline weather for the sandy clay loam soil (TAW = 120 mm m^{-1}) are shown in Table 9-2. Significant differences in mean yield but no significant differences in distribution of the yields over the years were observed. For the length of growing cycle, no differences were observed.

Table 9-2: mean differences and Kolmogorov-Smirnov Z-statistic for baseline yield and length of growing cycle between observed and generated weather inputs

Crop	Yield (t ha^{-1})	Cycle (days).
t-test (difference of means and significance of test)		
Maize	0.9*	-6
Sorghum	0.5**	-4
KS-test (Z-statistic and significance of difference)		
Maize	1.42	1.27
Sorghum	1.16	1.50

*$p < 0.05$; **$p < 0.01$

An overestimation in both maize (0.9 t ha^{-1}) and sorghum (0.5 t ha^{-1}) yield was observed. This is likely coming from the effect of reduced inter-annual variability in the generated data. This is due to the common phenomenon for most weather generators of over dispersion (Kim et al., 2012). Over dispersion in generated data leads to underrepresentation of the series of successive days with relatively high or low precipitation which is not the case in reality. This might lead to the omission of variance of precipitation data, especially in the growing season.

9.5.2 Evaluation of future crop yield to management strategy

9.5.2.1 Maize

Table 9-3 shows results of projected simulated maize yields for different field management strategies. Just like it was observed with simulations of historical yields (Chapter 8), rainfed yields from F1 are higher than for F0 and FM as expected. This is a result of high nutrient levels from full fertilizer application dose. Applying less fertilizer resulted in lower but more stable yields. It was noted that projected irrigated yields are much more stable and higher than the yield with other management practices (lower CV values). This is because the crop is under no soil water and fertility stress. The crop water requirement is satisfied all the time and the soil is fully fertilized hence a stable and high production is expected.

Table 9-3: Simulated projected mean maize yields for different management practice on different soil type

Cultivar	TAW (mm m^{-1})	Management	Years used	Mean (t ha^{-1})	Standard deviation	CV (%)
Early maturing (100 days)	80	F1	All	6.899	1.78	26
Early maturing (100 days)	80	F1	Non-failure only	7.090	1.43	20
Early maturing (100 days)	80	F0	All	4.883	1.16	24
Early maturing (100 days)	80	F0	Non-failure only	5.012	0.92	18
Early maturing (100 days)	80	FM	All	2.726	0.66	24
Early maturing (100 days)	80	FM	Non-failure only	2.819	0.40	14
Early maturing (100 days)	80	Irrigation	All	7.779	0.25	3
Early maturing (100 days)	120	F1	All	6.095	2.58	42
Early maturing (100 days)	120	F1	Non-failure only	6.978	1.19	17
Early maturing (100 days)	120	F0	All	4.375	1.75	40
Early maturing (100 days)	120	F0	Non-failure only	4.960	0.74	15
Early maturing (100 days)	120	FM	All	2.140	1.22	57
Early maturing (100 days)	120	FM	Non-failure only	2.770	0.78	28
Early maturing (100 days)	120	Irrigation	All	7.773	0.25	3
Early maturing (100 days)	160	F1	All	6.890	2.22	32
Early maturing (100 days)	160	F1	Non-failure only	7.490	1.00	19
Early maturing (100 days)	160	F0	All	4.809	1.47	31
Early maturing (100 days)	160	F0	Non-failure only	5.224	1.46	20
Early maturing (100 days)	160	FM	All	2.423	1.09	45
Early maturing (100 days)	160	FM	Non-failure only	2.900	2.90	21
Early maturing (100 days)	160	Irrigation	All	7.779	0.25	3
Medium maturing (120 days)	120	F1	All	7.000	3.62	47
Medium maturing (120 days)	120	F1	Non-failure only	8.113	2.20	27
Medium maturing (120 days)	120	F0	All	5.055	2.45	44
Medium maturing (120 days)	120	F0	Non-failure only	5.860	1.44	25
Medium maturing (120 days)	120	FM	All	2.543	1.48	58
Medium maturing (120 days)	120	FM	Non-failure only	3.316	0.972	29
Medium maturing (120 days)	120	Irrigation	All	9.627	0.35	4

TAW 80=Loamy sand; TAW 120=Sandy clay loam; TAW 160=Loam

The risks of rainfed farming can still be envisaged in the future given the high standard deviation and CV values. Climate variability and effects of El Niño (droughts and too much rains) are still expected to influence the climate of the region hence the rainfed yields will still be unstable if not well managed. The soil types also contribute to this variability (Table 9-3). Loamy sand soil had lower number of failure years compared to sandy clay loam and loam soils. This is due to the properties of the soil in holding water for plants to use.

Table 9-4 shows the number of failure years and their percentage of occurrence for different soil total available water (TAW) classes for different maize cultivars. It is observed that crops growing on a soil with a small TAW will regularly experience water stress and are likely to have a small canopy cover. As such they can more easily survive in long dry spells than crops growing on soils with large TAW. However, large TAW positively affects the survival rate of the crop. The occurrence of failure years almost doubled (from 7 to 12%) under future climate projections when compared to baseline climate (Table 8-2).

Table 9-4: Number of failure years with respect to different soil TAW class for maize

Cultivar	TAW (mm m^{-1})	Number of failure years	% of occurrence
Early maturing	80	3	3
	120	12	12
	160	7	7
Medium maturing	120	14	14

TAW 80=Loamy sand; TAW 120=Sandy clay loam; TAW 160=Loam

Table 9-5 shows results of simulated projected length of growing cycle and net irrigation requirement (Inet) for maize. It was observed that the length of growing cycle in the future is shorter than the baseline (Table 8-4). A 14 day reduction is observed in all (early, intermediate and late maturing) cultivars. This is due to the temperature increase in the projections which resulted in a quicker accumulation of growing degree days, hence a reduction of the length of the growing cycle. This reduction in length of growing cycle has implications for yield as less radiation can be intercepted. Lower Inet values are observed in all soils used than for the baseline period. With the projected temperature increase, there are high chances of an increase in soil temperature hence high rates of soil evaporation. This will end up making the soil lose a lot of water through evaporation, although this will depend on its hydraulic properties. More water will be required in the future to satisfy crop water requirement if irrigated maize is cultivated on it.

Table 9-5: Simulated future length of growing cycle and net irrigation requirement of maize on different types of soil

Cultivar	TAW (mm m^{-1})		Mean	Standard deviation	CV (%)
Early Maturing	80	Cycle (days)	86	4	5
		Inet (mm)	106	35	33
	120	Cycle (days)	86	4	5
		Inet (mm)	85	87	44
	160	Cycle (days)	86	4	5
		Inet (mm)	84	37	44
Medium maturing	120	Cycle (days)	104	4	4
		Inet (mm)	120	49	41

TAW 80=Loamy sand; TAW 120=Sandy clay loam; TAW 160=Loam

Projected maize yield and Inet changes compared to the baseline (under generated weather data) for different field management practices and soil types (TAW classes) are shown in Figure 9-2.

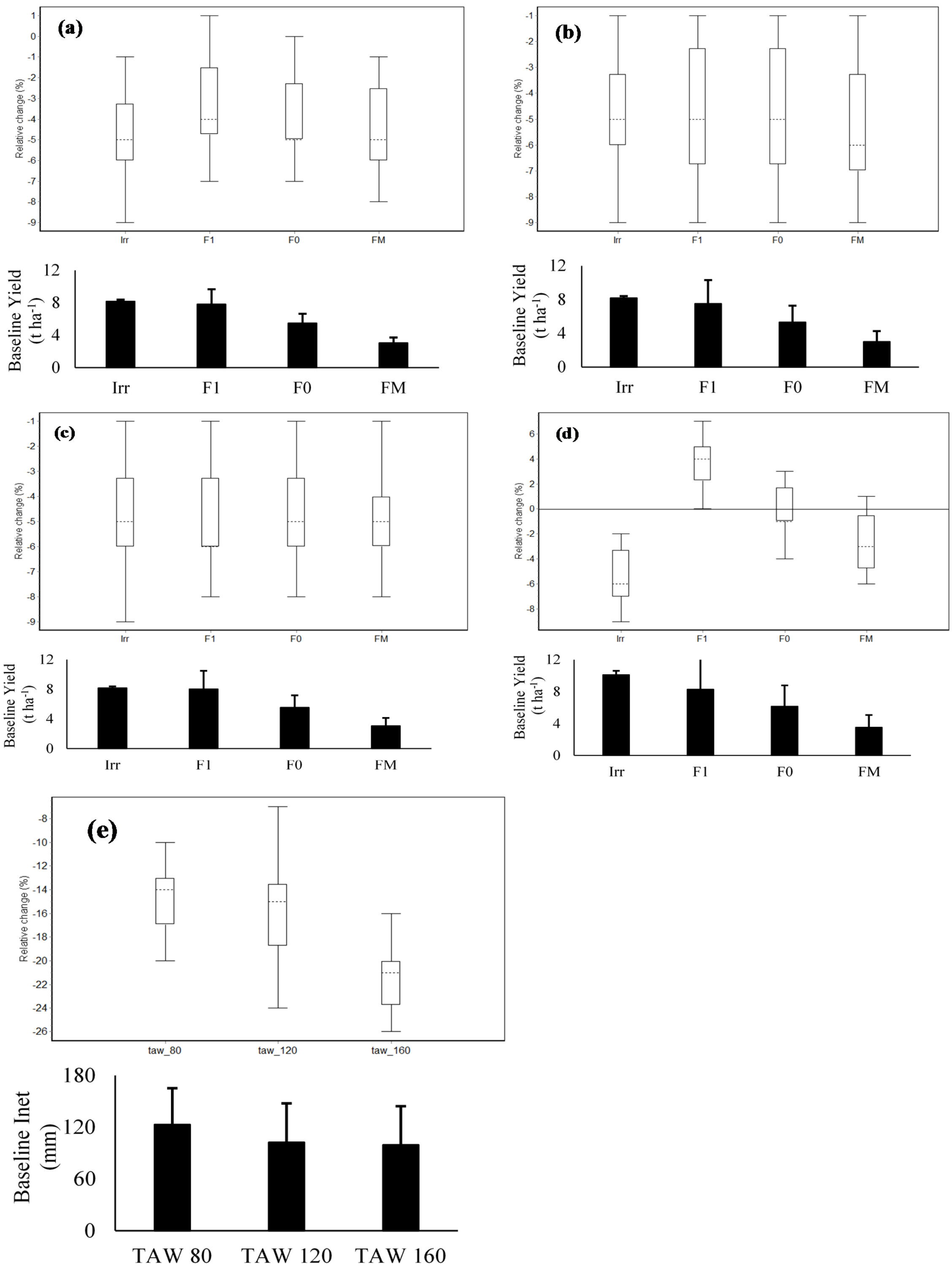

Figure 9-2: Projected maize yield changes under different field management on different soil types for early maturing cultivar; (a) = loamy sand; (b) = sandy clay loam; (c) = loam; and for intermediate maturing cultivar; (d) = sandy clay loam; (e) = net irrigation requirement for an early maturing cultivar.

A consistent decline in median projected yields on the three soil types for early maturing cultivar is observed. Median yield decline is higher in sandy clay loam (TAW 120 mm m^{-1}) between 2 to 7%. On sandy clay loam, yields of intermediate maturing cultivar with F1 management practice are projected to increase by 4% compared to the baseline. This probably follows from more radiation interception by an intermediate cultivar and water saving effects due to elevated [CO_2] (rather than direct production increases for this C4 crop) counterbalancing high temperature effects and detrimental effects on water availability. There is no change in projected yields under F0 management compared to the baseline. FM and

Irrigated yields are projected to decrease in the order of 4 to 6% when compared to the baseline yields. With limiting soil fertility, intermediate cultivars senescence before maturity is reached, hence they cannot profit from more radiation potential. The projected climatic changes decrease yield compared to the baseline.

Projected baseline yields follow the order of improved management conditions in all soil classes used. Higher yields are observed with irrigated and lower yields with FM. There is more stability in projected median maize yields with irrigation than rainfed. This is portrayed with the length of the error bars (error bars showing uncertainty in impact from projections). A consistent decline in future net irrigation requirement is observed compared to the baseline (Figure 9-2e). This is a result of the reduction of the length of growing cycle of crops in the future owing to the projected increase in temperature. This decline ranges from 14 to 20% in Inet for the future, from loamy sand to loam. As TAW increases, net irrigation requirement decreases. The decline in yield of early maturing cultivars was noted to be similar on all soil types (about 5%). The results indicate that shifting from early maturing cultivars to intermediate maturing cultivars gives higher yields, but only if well fertilized (F1).

9.5.2.2 Sorghum

Table 9-6 shows results of projected simulated sorghum yields for different field management strategies. Just like it was observed with simulations of projected maize yields, rainfed yields from F1 are higher than for F0 and FM as expected. This is a result of high nutrient levels from full fertilizer application dose. Stable yields were observed in simulations with lower fertility doses (that is, F0 and FM). Projected yields from irrigation management practices are much more stable and very high than the yield in other management practices (lower CV values). This is because the crop is under no soil water and fertility stress. The crop water requirement is satisfied all the time and the soil is fully fertilized hence a stable and high production is expected.

Table 9-6: Simulated projected mean sorghum yields for different management practice on different soil type

Cultivar	TAW ($mm\ m^{-1}$)	Management	Years used	Mean ($t\ ha^{-1}$)	Standard deviation	CV (%)
Early maturing (90 days)	80	F1	All	5.041	2.02	40
			Non-failure only	5.736	0.86	15
		F0	All	3.222	1.22	38
			Non-failure only	3.646	0.43	12
		FM	All	1.789	0.93	52
			Non-failure only	2.261	0.60	26
		Irrigation	All	6.083	0.17	3
Medium maturing (115 days)	80	F1	All	5.348	1.52	28
			Non-failure only	5.470	1.32	24
		F0	All	3.674	0.75	20
			Non-failure only	3.732	0.62	17
		FM	All	2.331	0.50	21
			Non-failure only	2.395	0.34	14
		Irrigation	All	6.159	0.23	4
	120	F1	All	4.915	2.01	41
			Non-failure only	5.576	0.95	17
		F0	All	3.299	1.26	38
			Non-failure only	3.743	0.37	10
		FM	All	1.869	0.99	53
			Non-failure only	2.366	0.62	26
		Irrigation	All	6.175	0.24	4
	160	F1	All	5.483	1.69	31
			Non-failure only	5.951	1.01	17
		F0	All	3.565	1.06	30
			Non-failure only	3.870	0.58	15
		FM	All	2.066	0.89	43
			Non-failure only	2.444	0.51	21
		Irrigation	All	6.176	0.24	4
Late maturing (120 days)	120	F1	All	5.407	2.44	45
			Non-failure only	6.176	1.52	25
		F0	All	3.630	1.48	41
			Non-failure only	4.121	0.74	18
		FM	All	2.026	1.11	55
			Non-failure only	2.570	0.71	27
		Irrigation	All	7.138	0.30	4

TAW 80=Loamy sand; TAW 120=Sandy clay loam; TAW 160=Loam

The high standard deviation and CV values observed, shows that the risks in rainfed farming can still be envisaged even for a drought resistant crop like sorghum. Climate variability and effects of El Niño (droughts and too much rains) are still expected to influence the climate of the region hence the rainfed yields will still be unstable if not well managed. The soil types also contribute to this variability (Table 9-7). Loamy sand soil had lower number of failure years compared to sandy clay loam and loam soils. Table 9-7 shows the number of failure years and their percentage of occurrence for different soil total available water (TAW) classes under different sorghum cultivars. As it was observed in maize, for sorghum, the occurrence of failure years almost doubled in the future when compared to baseline climate.

Table 9-7: Number of failure years with respect to different soil TAW class for sorghum

Cultivar	TAW ($mm\ m^{-1}$)	Number of failure years	% of occurrence
Early maturing	120	12	12
Medium maturing	80	2	2
	120	12	12
	160	8	8
Late maturing	120	12	12

TAW 80=Loamy sand; TAW 120=Sandy clay loam; TAW 160=Loam

Table 9-8 shows results of simulated projected length of growing cycle and net irrigation requirement (Inet) for sorghum. It is observed that the length of growing cycle in the future is shorter than the baseline period. A 10 day reduction is observed in all (early, intermediate and late maturing) cultivars. Just like in maize, the temperature increase in the projections which resulted in a quicker accumulation of growing degree days, hence a reduction of the length of the growing cycle. This reduction in length of growing cycle has implications for yield as less radiation can be intercepted. Lower Inet values are observed in all soils used than for the baseline period. With the projected temperature increase, this soil loses a lot of water due to its hydraulic properties. More water will be required in the future to satisfy crop water requirement if irrigated sorghum is cultivated on it.

Table 9-8: Simulated future length of growing cycle and net irrigation requirement of sorghum on different types of soil

Cultivar	**TAW (mm m^{-1})**		**Mean**	**Standard deviation**	**CV (%)**
Early Maturing	120	Cycle (days)	85	4	5
		Inet (mm)	82	37	45
Medium Maturing	80	Cycle (days)	101	3	3
		Inet (mm)	129	42	33
	120	Cycle (days)	101	3	3
		Inet (mm)	110	46	42
	160	Cycle (days)	101	3	3
		Inet (mm)	107	46	43
Late maturing	120	Cycle (days)	109	4	4
		Inet (mm)	127	52	41

TAW 80=Loamy sand; TAW 120=Sandy clay loam; TAW 160=Loam

Projected sorghum yield and Inet changes compared to the baseline (under generated weather data) for different field management practices and soil types (TAW classes) are shown in Figure 9-3.

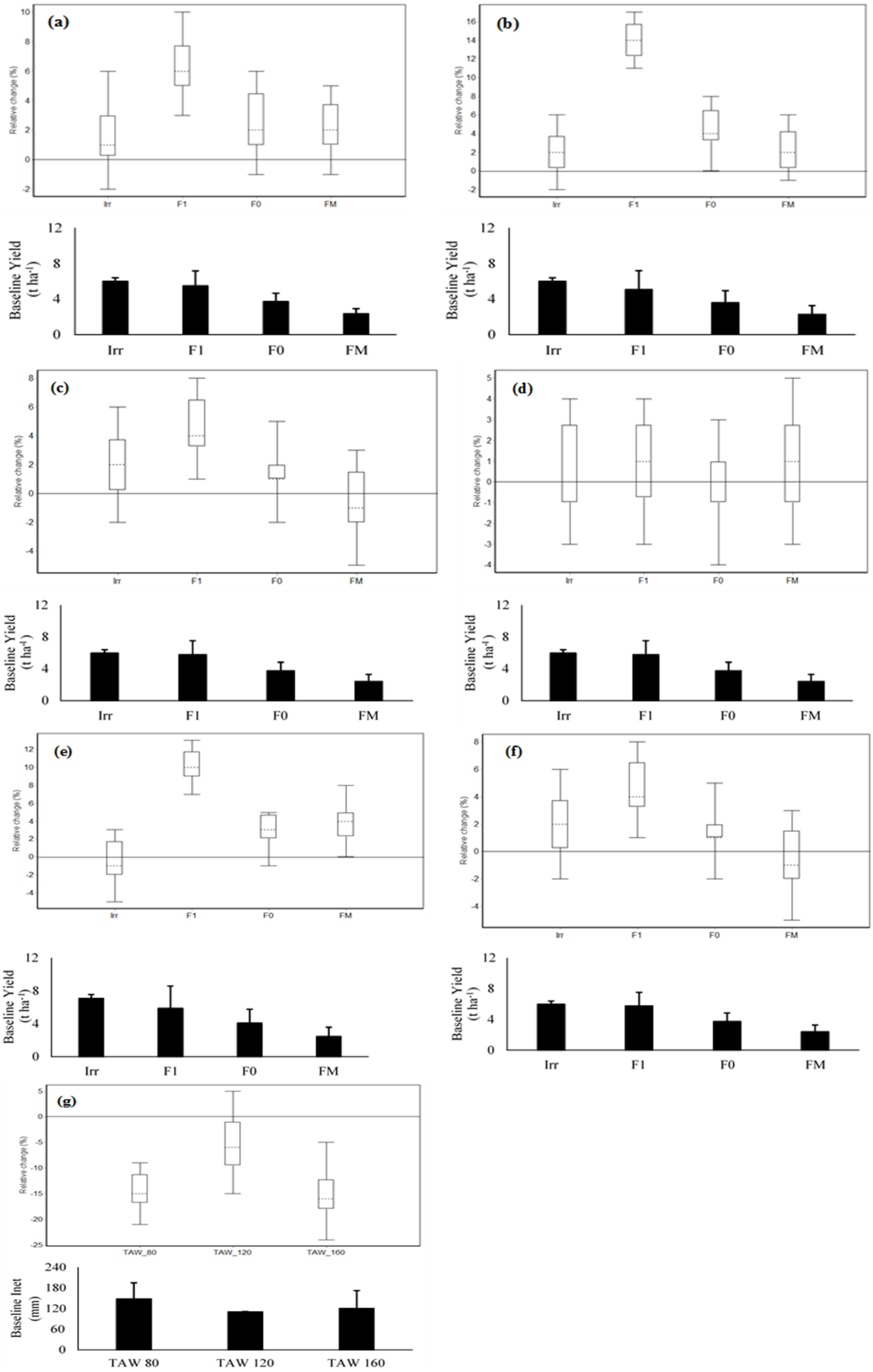

Figure 9-3: Projected sorghum yield changes under different field management on different soil types for intermediate maturing cultivar; (a) = loamy sand; (b) = sandy clay loam; (c) = loam: for early maturing cultivar; (d) = sandy clay loam: for late maturing cultivar; (e) = sandy clay loam; and for medium maturing cultivar; (f) = sandy clay loam. (g) = Projected net irrigation requirement for different types of soil under intermediate maturing cultivar.

A consistent increase in the median projected yields in all soil types is observed for intermediate and late maturing variety. On sandy clay loam, a general increase from 1 up to 14% is observed. A large increase is under F1 management followed by F0 and FM. Sorghum under irrigation have projected yields of an increase of about 2% are observed. Similar to maize, projected baseline yields follow the order of improving management conditions on all soil classes. Higher yields are observed with irrigation and lower yields with FM. There is more stability in projected median sorghum yields with irrigation than rainfed. Among the rainfed projected yields, FM has lower standard deviation, which means that the future yields from FM are more stable than F1 and F0. There is a general decrease in net irrigation requirement for the future for the three soil types due to beneficial changes in water availability and improved water use efficiency (decreased transpiration) under elevated [CO_2]. Loam soil has a median of 20% decrease with sandy clay loam of about 8%. The baseline Inet is more stable on sandy clay loam than the loam and loamy sand soils.

The increase in yield of intermediate maturing cultivar is affected by soil type. Higher yield increases are obtained on the 120 mm m^{-1} TAW class. For 160 mm m^{-1} TAW class, the yield might even decrease with farmers' management practices. In the 120 mm m^{-1} TAW class, early maturing cultivar resulted in a smaller yield increase than late and specifically intermediate maturing cultivars following associated difference in potential radiation interception.

9.5.3 Discussion

The impact assessment showed that the projected effect of climate change on crops in this study is highly crop specific with sorghum showing more positive effects than maize. The difference in response of the crops is due to the higher temperatures. Due to its higher tolerance to heat and water stress, it benefited more from a warmer and wetter climate. The soil types play a role with the sandy clay loam soils (TAW 120 mm m^{-1}) being more productive for sorghum. Both crops are C4 crops that do not benefit from increased [CO_2] for direct production stimulation. Yet, [CO_2] decreases transpiration and as such leads to indirect water saving effects.

The projected decline of yields for maize are largely consistent with studies in the south eastern African region, which are predominantly large scale Jones and Thornton (2003) and Thornton et al. (2011) projected that maize yields will likely decline in most countries in Southern Africa by an average of 10% and 16%, respectively by mid-21st century. Parry et al. (2004) projected a decline of 5-30% in cereals yields and Schlenker and Lobell (2010) projected a decline of up to 22%. In a study involving eight countries in Southern Africa, Hachigonta et al. (2013) also broadly projected a decline in crop yields. A local scale study by Zinyengere et al. (2014) projected a decrease of 5% for maize in Lilongwe using A2 SRES scenario. This is in line with the results of this research. Contrary to these results, Ngwira et al. (2014) projected increase in maize yields for Lilongwe using A1B scenarios. The reason for this was the use of improved soil and water conservation management practices, which were not implemented in this research. It is assumed that if these were implemented, increase in projected yields could have been attained.

However, for sorghum Schlenker and Lobell (2010) projected a decline of 17% for sorghum which is contrary to the results of this research. The reason might be the difference in the scale used to do the simulation. This study was more on a local scale while the research of Schlenker and Lobell (2010) was on very large scale.

In this research, different climate models were used and it was shown that predicted impacts differ among climate model projections. The representation of this uncertainty confirms that using only one or a limited number of climate models may not show a representative yield prediction for the future.

In this study, yield gains for maize and sorghum under irrigation were robustly apparent and stable. While applying fertilizer is important in increasing yields, incorporating farmer's practices in simulations is more rewarding as the farmers are usually risk averse and they will stick to their traditional practices even if a new technology is being implemented. Therefore, while results from this study globally agree with large scale studies in the region, it draws out the local validated field management and soil type specificity of impacts not necessarily accounted for by large scale studies.

The results have shown that irrigation plays a vital role in stabilising yields. In all simulations where irrigation was applied there were high and stable yields. This highlights the increased vulnerability of crops to drought increase in the future. Although this might be expensive and out of reach for smallholder farmers, the yield gains and benefit of stable yields might offset the high installation costs.

9.6 Conclusion

This study was able to demonstrate that impacts of climate change on maize and sorghum in Malawi will be significant, but vary according to field management practices, crop type and climate model. On various soils maize will be impacted negatively while sorghum will benefit from climate change. The early maturing cultivars will benefit more than the late maturing cultivars. Despite the small increase or decrease of yield, the occurrence of failure years will almost double with climate change. Given the yield overestimation under generated compared to observed baseline weather, the yield decline of maize might be larger and the yield increase of sorghum smaller than simulated here. The study showed that local farmer field management practices could help minimise the possible adverse impacts of climate change if additional factors are added (more fertilizer, hybrid cultivars) to take advantage of potential benefits.
The projected rather small yield decline of about 5% for maize and the yield increase of 2 up to 10% for sorghum contradicts the predicted sharp decline for cereals in Southern Africa byCane et al. (1994) and Stige et al. (2006).

Part V Conclusion and Perspectives

Chapter 10
General conclusions and recommendations

10.1 General conclusions

The main objective of this research was to evaluate sustainable management for stabilizing and increasing cereal yield production of small-scale farmers in Malawi in current and future climatic conditions. Therefore four research questions were formulated, which are answered and discussed hereafter.

10.1.1 Research question 1. What has been the trend of rainfall in the past three decades in Malawi and its effects on the length of growing period (LGP)?

Analysis of the characteristics of the growing season in central Malawi has shown significant changes in the onset, cessation and LGP. There is a clear delayed onset and advanced cessation in most studied locations and shorter LGP with time within the period considered (1980 to 2009). This agrees with farmers' perception.

Contrary to what can be expected from the rainfall analysis only, simulation results obtained with a crop growth model fine-tuned for Malawi (see research question 3), later revealed that the average yield for the second half of the considered period (1995-2009) might not drop below the average yield for the first half of the considered period (1980-1994). Simulations indicated instead even a slight yield increase. This demonstrates the potential of crop water productivity models which simulate a dynamic crop response to the environment (weather, soil, management). Explanation for the contra-intuitive difference between LGP and yield can be given by the fact that water stress early in the growing season may keep the crop's canopy cover small, which results in more chances for the crop to survive in later long dry spells. The BUDGET model, used for the assessment of the LGP, lacks that dynamic crop response.

10.1.2 Research question 2. What are the future climate change projections for Malawi for the 2050's?

Stochastically downscaled climatic change factors from 15 GCMs forced under the A1B emission scenario agreed on an increase of around 1.8°C for future temperature. Still, individual model projections diverted between 1°C to just above 2°C. These results compare well with projections for the southern African region. With temperature, also the evaporating power of the atmosphere (ET_o) will increase. An average increase of 3.4% was predicted, ranging from +1.6% up to +6.0% for the different GCMs.

The ensemble median projected a decrease in monthly precipitation totals in the first two months of the growing season and an increase in the last three months of the growing season. Projections of different climate models varied between a 10% increase and a 5% decrease in monthly rainfall, which is illustrative for the high uncertainty in rainfall projections in the area. This differential behaviour of climate models has been reported in climate change reports of mixed responses of models in southern Africa.

By downscaling climate factors to local weather data and generating long series of future weather data with the stochastic weather generator LARS-WG climate temporal variability and extremes were included in the future data, which allows for risk assessment.

10.1.3 Research question 3. Is AquaCrop capable of simulating crop growth and development on soils with different fertility levels for maize (*Zea mays* L.) and sorghum (Sorghum *bicolor* L. Moech) in two contrasting climates in Malawi?

To address food security and assess the effect of environment and management on crop production, FAO developed AquaCrop. When designing the model, an optimum balance between simplicity, accuracy and robustness was pursued. To be widely applicable AquaCrop uses only a relatively small number of explicit parameters and mostly-intuitive input-variables requiring simple methods for their determination. On the other hand, the calculation procedures are grounded on basic and often complex biophysical processes to guarantee an accurate simulation of the response of the crop in the plant-soil system. For these purposes the AquaCrop model was selected and evaluated in this research.

Field experiments with maize and sorghum were set up at two locations (Bunda and Kasinthula) for three successive growing seasons to investigate the effect of water and soil fertility stresses and to fine-tune the AquaCrop model to the Malawian environment. The growing seasons were different in rainfall, although for Bunda all seasons were classified as wet, while for Kasinthula they were classified as a dry, wet and normal. The recommended fertilizer application rate by the government (F1) and half of the recommended rate (F0) were considered. For both cereals, experiments were carried out for three cultivars that differ in the length of the growing cycle (early, intermediate and late maturing cultivars). The experimental data of the full recommended fertilizer application rate treatments (F1) from the 2010/11 growing season (no water stress assumed) were used to fine tune the AquaCrop model. The half recommended fertilizer application rate treatments (F0) were used for soil fertility stress calibration. Model validation used data from the 2011/12 and 2012/13 growing seasons.

After fine-tuning the crop parameters, the validation showed that the model performed well in both sites. The r^2 (Pearson correlation coefficient) was high for above-ground biomass (B), soil water content in the root zone (SWC), canopy cover (CC) and grain yield (Y) in the two sites with values over 90%. The model performed excellent in simulating B, SWC, CC and Y with RRMSE (relative root mean square error) values less 10% except for maize biomass and yield at Bunda and sorghum biomass at Kasinthula which were just above 10% (still considered as excellent). As for EF (Nash-Sutcliffe model efficiency coefficient), the model performed well for all parameters under test: B, SWC, CC and Y were close to 1.

Although AquaCrop was successfully calibrated and validated for maize and sorghum, the observed and simulated yields for the three seasons were far above the farmer reported yields. The socio-economic analysis revealed that fewer farmers are capable of applying the government recommended rate of fertilizers (F1). Even by applying only half of the recommended rate (F0), simulated yields are still twice as high as the reported farmers yields. Therefore an FM strategy was introduced, which refers to farmers rate of application. Even with this fertility management the yields were still slightly above farmers yield. It was assumed that this might be due to the underestimation of yields reported by farmers, and to the AquaCrop version used, which does not simulate the effect of pest, diseases and weed on yield.

10.1.4 Research question 4. What is the potential impact of future climate change for the 2050s on crop production in Malawi?

This question was answered by running simulations with the generated future weather data using the fine-tuned AquaCrop for the Malawian environment.

First, simulated yields under generated baseline weather were compared with simulated yields under observed weather to assess the representativeness of generated weather data with LARS-WG. Although there was a significant overestimation of the mean yield, probably due to over dispersion of generated climate data, hence underrepresentation of dry spells, no significant differences in yield distribution over the years were observed between observed and generated weather data.

The study of the potential influence of future climate change projected by a multi-model ensemble of climate models for the 2050s on crop production in Malawi indicated that maize production is impacted negatively while sorghum will benefit from climate change. The predicted relatively small yield decline of about 5% for maize and yield increase of 2 up to 10% for sorghum contradicts the often predicted sharp decline for cereals in southern Africa. Given the detected underrepresentation of dry spells in generated weather data, the yield decline of maize might be larger and the yield increase of sorghum smaller than simulated. Depending on the soil type and cultivar, the numbers vary a bit, but the general trends remain valid. Differences between impacts simulated under projections of different climate models show that studies using only one or a limited number of climate models may not represent the full range of impacts to be expected.

Despite the 3.4% increase in ET_o and the 3% decrease in rainfall, crop yields in the future climatic conditions can be higher than the actual yields. This is due to the CO_2 fertilization which will increase the crop water productivity of the cereals (C4 crops) by 10% in the 2050's. This requires an adjustment of the current fertilizer application rates.

Although high (F1) and medium (F0) fertilizer application rates, might give higher yields than the current farmers application rates (FM), the risk-averse farmers might stick to their FM strategy due to its higher yield stability. Applying more fertilizers (F1 or F0) results in (much) higher yields in rainy years but also in possible lower yields and even complete failure in dry years.

Finally, it has to be noted that despite the small increase or decrease of yield, the occurrence of failure years will almost double from 0.7 year out of 10, to 1.2 years out of 10 with climate change. This is more important for the small holder farmers than the slight increase/decrease of mean crop yields. Given that only 14% of the potential area is irrigated, the problem of failure years can theoretically be solved by expanding the area under irrigation. This might be feasible since the net irrigation requirement account for roughly only 20% of the seasonal crop water requirements. By introducing irrigation farmers can obtain a high and stable yield, especially if they start cultivating higher yielding cultivars than the current mix of composite and traditional land races. However, irrigation is only an option for the smallholder farmers if the government supports its introduction.

10.1.5 Conclusion

The research indicates that yields might be increased by a better field management and especially by applying at least the government recommended fertilizer rates. However, this has to go hand in hand with an introduction of irrigation, since the number of failure years under rainfed agriculture for the future as well the actual weather conditions is far too high. Once irrigation is available, the cultivation of high yielding cultivars is recommended.

10.2 Recommendations

Given that irrigated agriculture is essential for the improvement and stabilization of crop yields, proper irrigation calendars should be developed. To avoid misuse of water, extension services have to train farmers in design and water management of irrigated agriculture. In the more arid regions, constraint on the water resources might limit the area of land that can be irrigated. For those regions, the benefits of deficit irrigation should be studied. Current research indicates that with a well-designed deficit irrigation strategy, crop yields might (nearly) double with the same amount of water. This can only be achieved if sufficient land is available for irrigation and that farmers are willing to cooperate, since under deficit irrigation the yield per unit of land decreases.

Due to the absence of long series of daily climate data in other agro-ecological zones (AEZ), the research on the effect of climate change was restricted to Lilongwe in the plateau AEZ. The research should be extended to other AEZs, especially the Lower Shire plains should be considered since it has a more arid character. In this research AquaCrop was fine-tuned to and validated for this AEZ, but simulations could not be run due to climatic data constraints. The research can also be extended to the Highlands, Rift Valley escarpment and the Lakeshore Plains given their importance for agriculture. It is believed that the fine-tuned AquaCrop will also perform well in these more humid environments.

If the research on the effect of climate change is expanded to the more arid Lower Shire plains, it is necessary to test if AquaCrop is able to simulate the effect of field surface practices which encourage rainwater harvesting. Since weed infestation can be important in some fields, it might be worthwhile to run the future version of AquaCrop which will include the effect of weeds on crop yield.

The research might gain accuracy if regional climate models (RCM) are available for the region. Additionally, further precision can be expected if the research can be done with projections based on the newly released climate change scenarios, the Representative Concentration Pathways (RCP) (Stocker et al., 2013).

References

Abrha, B., Delbecque, N., Raes, D., Tsegay, A., Todorovic, M., Heng, L., Vanutrecht, E., Geerts, S., Garcia-Vila, M., and Deckers, S. (2012). Sowing Strategies for Barley (Hordeum Vulgare L.) Based on modelled yield response to water with AquaCrop. *Experimental Agriculture* **48**, 252-271.

Adiku, S. G. K., Dayananda, P. W. A., Rose, C. W., and Dowuona, G. N. N. (1997). An analysis of the within-season rainfall characteristics and simulation of the daily rainfall in two savanna zones in Ghana. *Agricultural and Forest Meteorology* **86**, 51-62.

AGRHYMET (1996). Methodologie de suivi des zones a risque. *AGRHYMET FLASH, Bulletin de Suivi de la Campagne Agricole au Sahel, Centre Regional AGRHYMET, B.P. 11011, Niamey, Niger* **2**, 2 pages.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO, Rome* **300**, 6541.

Alwang, J., and Siegel, P. B. (1999). Labor Shortages on Small Landholdings in Malawi: Implications for Policy Reforms. *World Development* **27**, 1461-1475.

Anderson, J. L., Balaji, V., Broccoli, A. J., Cooke, W. F., Delworth, T. L., Dixon, K. W., Donner, L. J., Dunne, K. A., Freidenreich, S. M., Garner, S. T., Gudgel, R. G., Gordon, C. T., Held, I. M., Hemler, R. S., Horowitz, L. W., Klein, S. A., Knutson, T. R., Kushner, P. J., Langenhost, A. R., Lau, N. C., Liang, Z., Malyshev, S. L., Milly, P. C. D., Nath, M. J., Ploshay, J. J., Ramaswamy, V., Schwarzkopf, M. D., Shevliakova, E., Sirutis, J. J., Soden, B. J., Stern, W. F., Thompson, L. A., Wilson, R. J., Wittenberg, A. T., Wyman, B. L., and Dev, G. G. A. M. (2004). The new GFDL global atmosphere and land model AM2-LM2: Evaluation with prescribed SST simulations. *Journal of Climate* **17**, 4641-4673.

Baron, C., Sultan, B., Balme, M., Sarr, B., Traore, S., Lebel, T., Janicot, S., and Dingkuhn, M. (2005). "From GCM grid cell to agricultural plot: scale issues affecting modelling of climate impact."

Batisani, N., and Yarnal, B. (2010). Rainfall variability and trends in semi-arid Botswana: Implications for climate change adaptation policy. *Applied Geography* **30**, 483-489.

Bharwani, S., Bithell, M., Downing, T. E., New, M., Washington, R., and Ziervogel, G. (2005). Multi-agent modelling of climate outlooks and food security on a community garden scheme in Limpopo, South Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 2183-2194.

Black, C. (1965). Particle fractionation and particle-size analysis. pp. 550-551. American Society of Agronomy Madison.

Boogaard, H., Van Diepen, C., Rötter, R., Cabrera, J., and Van Laar, H. (1998). "WOFOST 7.1: user's guide for the WOFOST 7.1 crop growth simulation model and WOFOST Control Center 1.5," DLO Winand Staring Centre Wageningen.

Boote, K. J., Jones, J. W., and Pickering, N. B. (1996). Potential uses and limitations of crop models. *Agronomy Journal* **88**, 704-716.

Cane, M. A., Eshel, G., and Buckland, R. (1994). Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea surface temperature. *Nature* **370**, 204-205.

Carbone, G. J., Mearns, L. O., Mavromatis, T., Sadler, E. J., and Stooksbury, D. (2003). Evaluating CROPGRO-Soybean performance for use in climate impact studies. *Agronomy Journal* **95**, 537-544.

Challinor, A., Wheeler, T., Craufurd, P., Ferro, C., and Stephenson, D. (2007). Adaptation of crops to climate change through genotypic responses to mean and extreme temperatures. *Agriculture, ecosystems & environment* **119**, 190-204.

Chirwa, E. W. (2005). Adoption of fertiliser and hybrid seeds by smallholder maize farmers in Southern Malawi. *Development Southern Africa* **22**, 1-12.

Collins, W. D., Bitz, C. M., Blackmon, M. L., Bonan, G. B., Bretherton, C. S., Carton, J. A., Chang, P., Doney, S. C., Hack, J. J., and Henderson, T. B. (2006). The community climate system model version 3 (CCSM3). *Journal of Climate* **19**, 2122-2143.

Cook, S., Gichuki, F., and Turral, H. (2006). Agricultural Water Productivity: Issues, Concepts and Approaches. Basin Focal Project Working Paper No.1.

Cooper, P. J. M., Dimes, J., Rao, K. P. C., Shapiro, B., Shiferaw, B., and Twomlow, S. (2008). Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture, Ecosystems & Environment* **126**, 24-35.

CSMD (2005). An introduction to the first general operational climate model at the National Climate Center. *Advances in Climate System Modelling 1*. National Climate Center, China Meteorological Administration, Beijing.

Day, P. R. (1965). Particle fractionation and particle-size analysis. *In* "Methods of soil analysis, Part 1" (C. Black, ed.), pp. 545-567. American Society of Agronomy, Inc, Madison, Wisconsin.

Déqué, M., Dreveton, C., Braun, A., and Cariolle, D. (1994). The ARPEGE/IFS atmosphere model - a contribution to the French community climate modeling. *Climate Dynamics* **10**, 249-266.

Dibike, Y. B., and Coulibaly, P. (2005). Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models. *Journal of Hydrology* **307**, 145-163.

DoI-MoAFS (1992). Small-Scale Irrigation in Malawi. Staff Appraisal Report. Agricultural Services Project. Department Of Irrigation, Ministry of Agriculture, Lilongwe.

Doorenbos, J., and Kassam, A. H. (1979). "Yield response to water. FAO Irrigation and Drainage Paper No. 33, Rome, Italy ".

Draper, N. R., and Smith, H. (1998). "Applied regression analysis," 3/Ed. Wiley-interscience Publication.

Dubrovský, M., Buchtele, J., and Žalud, Z. (2004). High-Frequency and Low-Frequency Variability in Stochastic Daily Weather Generator and Its Effect on Agricultural and Hydrologic Modelling. *Climatic Change* **63**, 145-179.

Fandika, I. R., Kadyampakeni, D., Bottomani, C., and Kakhlwa, H. (2007). Comparative response of varied irrigated maize to organic and inorganic fertilizer application. *Physics and Chemistry of the Earth* **32**, 1107-1116.

FAO (1995). Status of Sulphur in Soils and Plants of Thirty Countries. World Resources Report 79. Rome Italy.

FAO (2003). Unlocking the water potential of agriculture. Food and Agriculture Organisation of the United Nations, Rome Italy.

FAO (2004). Fertilizer consumption in 38 nations of sub-saharan Africa.

FAO (2005). New_LocClim: Local Climate Estimator. *Environment and Natural Resources Working Paper No. 20 (CD-ROM). FAO, Rome.*

FAO (2012a). ETo Calculator v. 3.2. *In* "Land and water digital media series No. 36". FAO, Rome, Italy.

FAO (2012b). FAOSTAT: Production-Crops, 2011 data, available at: http://faostat3.fao.org/home/E last accessed: 15/11/2014.

Fatichi, S., Ivanov, V. Y., and Caporali, E. (2011). Simulation of future climate scenarios with a weather generator. *Advances in Water Resources* **34**, 448-467.

Fischer, G., Shah, M., Tubiello, F. N., and Van Velhuizen, H. (2005). Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 2067-2083.

Fowler, H. J., Blenkinsop, S., and Tebaldi, C. (2007). Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *International Journal of Climatology* **27**, 1547-1578.

Fowler, H. J., Kilsby, C. G., O'Connell, P. E., and Burton, A. (2005). A weather-type conditioned multi-site stochastic rainfall model for the generation of scenarios of climatic variability and change. *Journal of Hydrology* **308**, 50-66.

Frenken, K. (2005). "Irrigation in Africa in figures: AQUASTAT survey-2005," Food & Agriculture Organisation of the United Nations (FAO), Rome, Italy.

Galin, V. Y., Volodin, E., and Smyshlyaev, S. (2003). Atmospheric general circulation model of INM RAS with ozone dynamics. *Russian meteorology and hydrology* **5**, 13-22.

García-Vila, M., Fereres, E., Mateos, L., Orgaz, F., and Steduto, P. (2009). Deficit irrigation optimization of cotton with AquaCrop. *Agronomy journal* **101**, 477-487.

Geerts, S., Raes, D., and Garcia, M. (2010). Using AquaCrop to derive deficit irrigation schedules. *Agricultural Water Management* **98**, 213-216.

Geerts, S., Raes, D., Garcia, M., Miranda, R., Cusicanqui, J. A., Taboada, C., Mendoza, J., Huanca, R., Mamani, A., Condori, O., Mamani, J., Morales, B., Osco, V., and Steduto, P. (2009). Simulating Yield Response of Quinoa to Water Availability with AquaCrop. *Agronomy Journal* **101**, 499-508.

GoM (2014). Agrometeorological Bulletins. Malawi Government, Ministry of Natural Resources, Energy and Environment. Department of Climate Change and Meteorological Services. http://www.metmalawi.com/bulletins/bulletins.php (accessed 04 Aug 2014).

Gordon, H. B., Rotstayn, L. D., McGregor, J. L., Dix, M. R., Kowalczyk, E. A., O'Farrell, S. P., Waterman, L. J., Hirst, A. C., Wilson, S. G., Collier, M. A., Watterson, I. G., and Elliott, T. I. (2002). "The CSIRO Mk3 Climate System Model. CSIRO, Aspendale. 130 pp."

Hachigonta, S., Nelson, G. C., Thomas, T. S., and Sibanda, L. M. (2013). Southern African Agriculture and Climate Change. IPFRI, Washington, DC.

Hachigonta, S., Reason, J. C., and Tadross, M. (2008). An analysis of onset date and rainy season duration over Zambia. *Theoretical and applied climatology* **91**, 229-243.

Hadgu, G., Tesfaye, K., Mamo, G., and Kassa, B. (2013). Trend and variability of rainfall in Tigray, Northern Ethiopia: Analysis of meteorological data and farmers' perception. *Academia Journal of Environmental Sciences* **1**, 159-171.

Harrison, L., Michaelsen, J., Funk, C., and Husak, G. (2011). Effects of temperature changes on maize production in Mozambique. *Climate Research* **46**, 211-222.

Hartkamp, A. D., White, J. W., and Hoogenboom, G. (2003). Comparison of three weather generators for crop modeling: a case study for subtropical environments. *Agricultural Systems* **76**, 539-560.

Hasumi, H., and Emori, S. (2004). " K-1 coupled model (MIROC) description." University of Tokyo, Tokyo.

Hewitson, B., and Crane, R. (2002). Self-organizing maps: applications to synoptic climatology. *Climate Research* **22**, 13-26.

Hewitson, B. C. (2003). Developing perturbations for climate change impact assessment. *EOS* **84**, 337-348.

Hewitson, B. C., and Crane, R. G. (2005). Gridded area-averaged daily precipitation via conditional interpolation. *Journal of Climate* **18**, 41-57.

Hewitson, B. C., and Crane, R. G. (2006). Consensus between GCM climate change projections with empirical downscaling: Precipitation downscaling over South Africa. *International Journal of Climatology* **26**, 1315-1337.

Hoerling, M., Hurrell, J., Eischeid, J., and Phillips, A. (2006). Detection and attribution of twentieth-century northern and southern African rainfall change. *Journal of Climate* **19**, 3989-4008.

Holzworth, D. P., Huth, N. I., deVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., Chenu, K., van Oosterom, E. J., Snow, V., Murphy, C., Moore, A. D., Brown, H., Whish, J. P. M., Verrall, S., Fainges, J., Bell, L. W., Peake, A. S., Poulton, P. L., Hochman, Z., Thorburn, P. J., Gaydon, D. S., Dalgliesh, N. P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F. Y., Wang, E., Hammer, G. L., Robertson, M. J., Dimes, J. P., Whitbread, A. M., Hunt, J., van Rees, H., McClelland, T., Carberry, P. S., Hargreaves, J. N. G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., and Keating, B. A. (2014). APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software* **62**, 327-350.

Hourdin, F., Musat, I., Bony, S., Braconnot, P., Codron, F., Dufresne, J.-L., Fairhead, L., Filiberti, M.-A., Friedlingstein, P., and Grandpeix, J.-Y. (2006). The LMDZ4 general circulation model: climate performance and sensitivity to parametrized physics with emphasis on tropical convection. *Climate Dynamics* **27**, 787-813.

Hsiao, T. C., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., and Fereres, E. (2009). AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: III. Parameterization and Testing for Maize. *Agronomy Journal* **101**, 448-459.

Hudson, D. A. (1998). Antarctic sea-ice extent, southern hemisphere circulation and South African rainfall, University of Capetown.

IBM (2013). IBM SPSS Statistics for Windows. IBM Corp., Armonk, NY.

Ikerra, S., Maghembe, J., Smithson, P., and Buresh, R. (1999). Soil nitrogen dynamics and relationships with maize yields in a gliricidia–maize intercrop in Malawi. *Plant and Soil* **211**, 155-164.

IPCC (2007). Climate Change: 2007 synthesis report. *Contribution of working group I,II, and II to the fourth Assessment report of the Intergovernmental Panel on Climate Change.* IPCC, Geneva. 51.

IPCC (2014). "Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," Cambridge University Press.

Irmak, A., Jones, J. W., and Jagtap, S. S. (2005). Evaluation of the CROPGRO-soybean model for assessing climate impacts on regional soybean yields. *Transactions of the Asae* **48**, 2343-2353.

Jacovides, C. P., and Kontoyiannis, H. (1995). Statistical procedures for the evaluation of evapotranspiration computing models. *Agricultural Water Management* **27**, 365-371.

Jamieson, P. D., Porter, J. R., and Wilson, D. R. (1991). A test of the computer-simulation model ARCHWHEAT1 on wheat crops grown in New-Zealand. *Field Crops Research* **27**, 337-350.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., and Ritchie, J. T. (2003a). The DSSAT cropping system model. *European Journal of Agronomy* **18**, 235-265.

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., and Ritchie, J. T. (2003b). The DSSAT cropping system model. *European Journal of Agronomy* **18**, 235-265.

Jones, P. G., and Thornton, P. K. (2003). The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change* **13**, 51-59.

Jury, M. R., and Mwafulirwa, N. D. (2002). Climate variability in Malawi, part 1: Dry summers, statistical associations and predictability. *International Journal of Climatology* **22**, 1289-1302.

Kadyampakeni, D. M. (2013). Comparative Response of Cabbage to Irrigation in Southern Malawi. *Journal of Agricultural Science* **5**.

Kahinda, J.-m. M., Rockstrom, J., Taigbenu, A. E., and Dimes, J. (2007). Rainwater harvesting to enhance water productivity of rainfed agriculture in the semi-arid Zimbabwe. *Physics and Chemistry of the Earth* **32**, 1068-1073.

Karcher, D. E., and Richardson, M. D. (2005). Batch analysis of digital images to evaluate turfgrass characteristics. *Crop Science* **45**, 1536-1539.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., McCown, R. L., Freebairn, D. M., and Smith, C. J. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* **18**, 267-288.

Kendall, M. G. (1975). Rank correlation methods, 4th ed. Charles Griffin, London.

Kiehl, J., Hack, J., Bonan, G., Boville, B., Williamson, D., and Rasch, P. (1998). The national center for atmospheric research community climate model: CCM3. *Journal of Climate* **11**, 1131-1149.

Kiehl, J. T., and Gent, P. R. (2004). The community climate system model, version 2. *Journal of Climate* **17**, 3666-3682.

Kiely, G. (1999). Climate change in Ireland from precipitation and streamflow observations. *Advances in Water Resources* **23**, 141-151.

Kijne, J. W., Barker, R., and Molden, D. (2003). Improving water productivity in agriculture: Editors' Overview. *Water productivity in agriculture: Limits and opportunities for improvement*.

Kilsby, C. G., Jones, P. D., Burton, A., Ford, A. C., Fowler, H. J., Harpham, C., James, P., Smith, A., and Wilby, R. L. (2007). A daily weather generator for use in climate change studies. *Environmental Modelling & Software* **22**, 1705-1719.

Kim, Y., Katz, R. W., Rajagopalan, B., Podesta, G. P., and Furrer, E. M. (2012). Reducing overdispersion in stochastic weather generators using a generalized linear modeling approach. *Climate Research* **53**, 13-24.

Krause, P., Boyle, D., and Bäse, F. (2005). Comparison of different efficiency criteria for hydrological model assessment. *Advances in Geosciences* **5**, 89-97.

Kulkarni, A., and Von Storch, H. (1995). Monte Carlo experiments on the effect of serial correlation on the Mann-Kendall test of trend. *Meteorologische Zeitschrift* **4**, 82-5.

Kurukulasuriya, P., and Mendelsohn, R. (2008). Crop switching as a strategy for adapting to climate change. *African Journal of Agricultural and Resource Economics* **2**, 105-126.

Legutke, S., and Voss, R. (1999). The Hamburg atmosphere-ocean coupled model ECHO-G. Technical Report No.18, German Climate Computer Center (DKRZ). [Online] http://mms.dkrz.de/pdf/klimadaten/models/ReportNo.18.pdf.

Lettenmaier, D. P., Wood, E. F., and Wallis, J. R. (1994). Hydro-Climatological Trends in the Continental United States, 1948-88. *Journal of Climate* **7**, 586-607.

Loague, K., and Green, R. E. (1991). Statistical and graphical methods for evaluating solute transport models: Overview and application. *Journal of Contaminant Hydrology* **7**, 51-73.

Loomis, R. S., Rabbinge, R., and Ng, E. (1979). Explanatory Models in Crop Physiology. *Annual Review of Plant Physiology and Plant Molecular Biology* **30**, 339-367.

Lowole, M. W. (1983). "Soils of Bunda College of Agriculture Estate." Bunda College of Agriculture, Lilongwe.

Lyon, B., and Mason, S. J. (2007). The 1997-98 summer rainfall season in southern Africa. Part I: Observations. *Journal of Climate* **20**, 5134-5148.

Lyon, B., and Mason, S. J. (2009). The 1997/98 Summer Rainfall Season in Southern Africa. Part II: Model Simulations and Coupled Model Forecasts. *Journal of Climate* **22**, 3802-3818.

Malmgren, B. A., and Winter, A. (1999). Climate zonation in Puerto Rico based on principal components analysis and an artificial neural network. *Journal of Climate* **12**, 977-985.

Mann, H. B. (1945). Nonparametric test against trend. Econometrica 13:245-259.

Martin, G., Ringer, M., Pope, V., Jones, A., Dearden, C., and Hinton, T. (2006). The physical properties of the atmosphere in the new Hadley Centre Global Environmental Model (HadGEM1). Part I: Model description and global climatology. *Journal of Climate* **19**, 1274-1301.

Materechera, S. A., and MlozaBanda, H. R. (1997). Soil penetration resistance, root growth and yield of maize as influenced by tillage system on ridges in Malawi. *Soil & Tillage Research* **41**, 13-24.

Mavromatis, T., and Hansen, J. W. (2001). Interannual variability characteristics and simulated crop response of four stochastic weather generators. *Agricultural and Forest Meteorology* **109**, 283-296.

McFarlane, N. A., Boer, G. J., Blanchet, J. P., and Lazare, M. (1992). The Canadian Climate Center 2nd-generation general-circulation model and its equilibrium climate. *Journal of Climate* **5**, 1013-1044.

McSweeney, C., New, M., Lizcano, G., and Lu, X. (2010). The UNDP Climate Change Country Profiles Improving the accessibility of Observed and Projected Climate Information for Studies of Climate Change in Developing Countries. *Bulletin of the American Meteorological Society* **91**, 157-166.

Meehl, G. A., Covey, C., Taylor, K. E., Delworth, T., Stouffer, R. J., Latif, M., McAvaney, B., and Mitchell, J. F. B. (2007). THE WCRP CMIP3 Multimodel Dataset: A New Era in Climate Change Research. *Bulletin of the American Meteorological Society* **88**, 1383-1394.

Mhizha, T., Geerts, S., Vanuytrecht, E., Makarau, A., and Raes, D. (2012). Relative transpiration as a decision tool in crop management: A case for rainfed maize in Zimbabwe. *African Crop Science Journal* **20**, 47-57.

MoAFS (2012). Guide to Agricultural Production and Natural Resources Management in Malawi. Ministry of Agriculture and Food Security, Department of Agricultural Extension Services, Lilongwe Malawi.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., and Kijne, J. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management* **97**, 528-535.

Monteith, J. L. (1996). The quest for balance in crop modeling. *Agronomy Journal* **88**, 695-697.

Mueller, C., Cramer, W., Hare, W. L., and Lotze-Campen, H. (2011). Climate change risks for African agriculture. *Proceedings of the National Academy of Sciences of the United States of America* **108**, 4313-4315.

Mugalavai, E. M., Kipkorir, E. C., Raes, D., and Rao, M. S. (2008). Analysis of rainfall onset, cessation and length of growing season for western Kenya. *Agricultural and Forest Meteorology* **148**, 1123-1135.

Mupangwa, W., Walker, S., and Twomlow, S. (2011). Start, end and dry spells of the growing season in semi-arid southern Zimbabwe. *Journal of Arid Environments* **75**, 1097-1104.

Nash, J. E., and Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology* **10**, 282-290.

Ngongondo, C., Xu, C.-Y., Gottschalk, L., and Alemaw, B. (2011). Evaluation of spatial and temporal characteristics of rainfall in Malawi: a case of data scarce region. *Theoretical and Applied Climatology* **106**, 79-93.

Ngwira, A. R., Aune, J. B., and Thierfelder, C. (2014). DSSAT modelling of conservation agriculture maize response to climate change in Malawi. *Soil & Tillage Research* **143**, 85-94.

Nkongolo, K. K., Chinthu, K. K. L., Malusi, M., and Vokhiwa, Z. (2008). Participatory variety selection and characterization of Sorghum (Sorghum bicolor (L.) Moench) elite accessions from Malawian gene pool using farmer and breeder knowledge. *African Journal of Agricultural Research* **3**, 273-283.

Nordhagen, S., and Pascual, U. (2013). The Impact of Climate Shocks on Seed Purchase Decisions in Malawi: Implications for Climate Change Adaptation. *World Development* **43**, 238-251.

NSO (2008). The 2008 Population and Housing Census. (N. S. Office, ed.). National Statistical Office, Zomba, Malawi.

NSO (2012). Integrated Household Survey 2010-2011: Household Socio-Economic Characterisctics Report. (N. S. Office, ed.). National Statistical Office, Zomba, Malawi.

Nyakudya, I. W., and Stroosnijder, L. (2011). Water management options based on rainfall analysis for rainfed maize (Zea mays L.) production in Rushinga district, Zimbabwe. *Agricultural Water Management* **98**, 1649-1659.

OCHA (2012). United Nations Office for the Coordination of Humanitarian Affairs (OCHA): Humanitarian Bulletin - Southern Africa. Issue No. 6. avialable at: http://www.unocha.org/ last accessed: 14/12/2013.

Ooms, A. (2012). Adaptation of smallholder farmers to climate change and its implication for cereal production in Malawi. M.Sc, KU Leuven University, Belgium.

Orr, A., and Ritchie, J. M. (2004). Learning from failure: smallholder farming systems and IPM in Malawi. *Agricultural Systems* **79**, 31-54.

Parry, M. L., Rosenzweig, C., Iglesias, A., Livermore, M., and Fischer, G. (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change* **14**, 53-67.

Passioura, J. B. (1996). Simulation models: Science; snake oil, education, or engineering? *Agronomy Journal* **88**, 690-694.

Peel, M. C., Finlayson, B. L., and McMahon, T. A. (2007). Updated world map of the Koppen-Geiger climate classification. *Hydrology and Earth System Sciences* **11**, 1633-1644.

Place, F., and Otsuka, K. (2001). Tenure, Agricultural Investment, and Productivity in the Customary Tenure Sector of Malawi. *Economic Development and Cultural Change* **50**, 77-100.

Pope, V., Gallani, M., Rowntree, P., and Stratton, R. (2000). The impact of new physical parametrizations in the Hadley Centre climate model: HadAM3. *Climate Dynamics* **16**, 123-146.

Pretty, J. N., Morison, J. I., and Hine, R. E. (2003). Reducing food poverty by increasing agricultural sustainability in developing countries. *Agriculture, ecosystems & environment* **95**, 217-234.

Prudhomme, C., Reynard, N., and Crooks, S. (2002). Downscaling of global climate models for flood frequency analysis: where are we now? *Hydrological Processes* **16**, 1137-1150.

Raes, D., Geerts, S., Kipkorir, E., Wellens, J., and Sahli, A. (2006a). Simulation of yield decline as a result of water stress with a robust soil water balance model. *Agricultural Water Management* **81**, 335-357.

Raes, D., Sithole, A., Makarau, A., and Milford, J. (2004). Evaluation of first planting dates recommended by criteria currently used in Zimbabwe. *Agricultural and Forest Meteorology* **125**, 177-185.

Raes, D., Steduto, P., Hsiao, T. C., and Fereres, E. (2009). AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: II. Main Algorithms and Software Description. *Agronomy Journal* **101**, 438-447.

Raes, D., Steduto, P., Hsiao, T. C., and Fereres, E. (2012). Crop Water Productivity. Calculation Procedures and Calibration Guide. AquaCrop version 4.0 reference manual. FAO Land and Water Development Division. Rome.

Raes, D., Willems, P., and Gbaguidi, F. (2006b). RAINBOW-A software package for hydrometeorological frequency analysis and testing the homogeneity of historical data sets. *In* "Proceedings of the 4th International Workshop on Sustainable management of marginal drylands", pp. 41-55.

Rhoades, J. D. (1982). Soil pH analysis. *In* "Methods of Soil Analysis, Part 2" (A. L. Page, R. H. Miller and D. R. Keeney, eds.). American Society of Agronomy, Inc, Madison.

Riha, S., Wilks, D., and Simoens, P. (1996). Impact of temperature and precipitation variability on crop model predictions. *Climatic Change* **32**, 293-311.

Ringer, M., Martin, G., Greeves, C., Hinton, T., James, P., Pope, V., Scaife, A., Stratton, R., Inness, P., and Slingo, J. (2006). The physical properties of the atmosphere in the new Hadley Centre Global Environmental Model (HadGEM1). Part II: Aspects of variability and regional climate. *Journal of climate* **19**, 1302-1326.

Rockström, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., and Qiang, Z. (2010). Managing water in rainfed agriculture—The need for a paradigm shift. *Agricultural Water Management* **97**, 543-550.

Roeckner, E., and Arpe, K. (1996). The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate. *Max-Planck-Institut für Meteorologie, Hamburg* **218**, 90.

Rosegrant, M. W., Tokgoz, S., and Bhandary, P. (2013). The New Normal? A Tighter Global Agricultural Supply and Demand Relation and Its Implications for Food Security. *American Journal of Agricultural Economics* **95**, 303-309.

Russell, G. L., Miller, J. R., and Rind, D. (1995). A coupled atmosphere-ocean model for transient climate change studies. *Atmosphere-ocean* **33**, 683-730.

SADC (2013). "State of Food Insecurity and Vulnerability in the Southern African Development Community (SADC)," Gaberone, Botswana.

Saka, A. R., Rao, P. S. C., and Sakala, W. D. (2003). Evaluating soil physical and chemical characteristics for describing nutrient leaching in agricultural soils. *Malawi Journal of Agricultural Sciences* **2**.

Sakala, W. D., Kumwenda, J. D. T., and Saka, A. R. (2003). The Potential of Green Manures to Increase Soil Fertility and Maize Yields in Malawi. *Biological Agriculture & Horticulture* **21**, 121-130.

Saxton, K., Rawls, W. J., Romberger, J., and Papendick, R. (1986). Estimating generalized soil-water characteristics from texture. *Soil Science Society of America Journal* **50**, 1031-1036.

Saxton, K. E. (2003). Soil water characteristics hydraulic properties calculator. http://hydrolab.arsusda.gov/soilwater/Index.htm.

Saxton, K. E., and Rawls, W. J. (2006). Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. *Soil Sci. Soc. Am. J.* **70**, 1569-1578.

Schlenker, W., and Lobell, D. B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters* **5**.

Schmidhuber, J., and Tubiello, F. N. (2007). Global food security under climate change. *Proceedings of the National Academy of Sciences* **104**, 19703-19708.

SeedCo (2009). SeedCo Product Manual 2010/11 SeedCo Limited, Harare. Zimbabwe.

Semenov, M. A. (2007). Development of high-resolution UKCIP02-based climate change scenarios in the UK. *Agricultural and Forest Meteorology* **144**, 127-138.

Semenov, M. A., and Barrow, E. M. (1997). Use of a stochastic weather generator in the development of climate change scenarios. *Climatic Change* **35**, 397-414.

Semenov, M. A., and Doblas-Reyes, F. J. (2007). Utility of dynamical seasonal forecasts in predicting crop yield. *Climate Research* **34**, 71-81.

Semenov, M. A., and Porter, J. R. (1995a). CLIMATIC VARIABILITY AND THE MODELING OF CROP YIELDS. *Agricultural and Forest Meteorology* **73**, 265-283.

Semenov, M. A., and Porter, J. R. (1995b). Non-linearity in climate change impact assessments. *Journal of Biogeography* **22**, 597-600.

Semenov, M. A., and Stratonovitch, P. (2010). Use of multi-model ensembles from global climate models for assessment of climate change impacts. *Climate Research* **41**, 1-14.

Shrestha, N. (2014). Improving cereal production in the Terai Region of Nepal: assessment of field management strategies through a model based approach, KULeuven University, Leuven.

Shrestha, N., Raes, D., Vanuytrecht, E., and Sah, S. K. (2013). Cereal yield stabilization in Terai (Nepal) by water and soil fertility management modeling. *Agricultural Water Management* **122**, 53-62.

Simelton, E., Quinn, C. H., Batisani, N., Dougill, A. J., Dyer, J. C., Fraser, E. D. G., Mkwambisi, D., Sallu, S., and Stringer, L. C. (2013). Is rainfall really changing? Farmers' perceptions, meteorological data, and policy implications. *Climate and Development* **5**, 123-138.

Slingo, J. M., Challinor, A. J., Hoskins, B. J., and Wheeler, T. R. (2005). Introduction: food crops in a changing climate. *Philosophical Transactions of the Royal Society B: Biological Sciences* **360**, 1983-1989.

Snapp, S. S. (1998). Soil nutrient status of smallholder farms in Malawi. *Communications in Soil Science and Plant Analysis* **29**, 2571-2588.

Snapp, S. S., Rohrbach, D. D., Simtowe, F., and Freeman, H. A. (2002). Sustainable soil management options for Malawi: can smallholder farmers grow more legumes? *Agriculture, Ecosystems & Environment* **91**, 159-174.

Stainforth, D. A., Aina, T., Christensen, C., Collins, M., Faull, N., Frame, D. J., Kettleborough, J. A., Knight, S., Martin, A., Murphy, J. M., Piani, C., Sexton, D., Smith, L. A., Spicer, R. A., Thorpe, A. J., and Allen, M. R. (2005). Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature* **433**, 403-406.

Steduto, P., Hsiao, T. C., Fereres, E., and Raes, D. (2012). Crop yield response to water. *FAO Irrigation and drainage paper* **66**.

Steduto, P., Hsiao, T. C., Raes, D., and Fereres, E. (2009). AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agronomy Journal* **101**, 426-437.

Stern, R., Knock, J., Rijks, D., and Dale, I. (2003). INSTAT Climatic Guide. http://www.reading.ac.uk/ssc/sofware/instat/climatic.pdf.

Stige, L. C., Stave, J., Chan, K.-S., Ciannelli, L., Pettorelli, N., Glantz, M., Herren, H. R., and Stenseth, N. C. (2006). The effect of climate variation on agro-pastoral production in Africa. *Proceedings of the National Academy of Sciences of the United States of America* **103**, 3049-3053.

Stocker, T., Qin, D., Plattner, G., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, B., and Midgley, B. (2013). IPCC, 2013: climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change.

Stockle, C. O., Martin, S. A., and Campbell, G. S. (1994). CROPSYST, A cropping systems simulation-model - water nitrogen budgets and crop yield. *Agricultural Systems* **46**, 335-359.

Stolt, J. (1997). Manual of soil physical measurements. Vol. 3, pp. 37, Wageningen, The Netherlands.

Tabari, H., Hosseinzadeh Talaee, P., Mousavi Nadoushani, S. S., Willems, P., and Marchetto, A. (2014). A survey of temperature and precipitation based aridity indices in Iran. *Quaternary International* **345**, 158-166.

Tadross, M., Suarez, P., Lotsch, A., Hachigonta, S., Mdoka, M., Unganai, L., Lucio, F., Kamdonyo, D., and Muchinda, M. (2009). Growing-season rainfall and scenarios of future change in southeast Africa: implications for cultivating maize. *Climate Research* **40**, 147-161.

Tadross, M. A., Hewitson, B. C., and Usman, M. T. (2005). The interannual variability of the onset of the maize growing season over South Africa and Zimbabwe. *Journal of Climate* **18**, 3356-3372.

Taye, M. T., and Willems, P. (2012). Temporal variability of hydroclimatic extremes in the Blue Nile basin. *Water Resources Research* **48**.

Tchale, H. (2009). The efficiency of smallholder agriculture in Malawi. *African Journal of Agriculture and Resource Economics* **3**, 101-121.

Thornton, P. K., Jones, P. G., Ericksen, P. J., and Challinor, A. J. (2011). "Agriculture and food systems in sub-Saharan Africa in a 4°C+ world."

Thornton, P. K., Jones, P. G., Owiyo, T., Kruska, R., Herrero, M., Kristjanson, P., Notenbaert, A., Bekele, N., and Omolo, A. (2006). Mapping climate vulnerability and poverty in Africa.

Todorovic, M., Albrizio, R., Zivotic, L., Saab, M.-T. A., Stockle, C., and Steduto, P. (2009). Assessment of AquaCrop, CropSyst, and WOFOST Models in the Simulation of Sunflower Growth under Different Water Regimes. *Agronomy Journal* **101**, 509-521.

Tsegay, A., Raes, D., Geerts, S., Vanuytrecht, E., Abraha, B., Deckers, J., Bauer, H., and Gebrehiwot, K. (2012). Unravelling crop water productivity of tef (eragrostis tef (zucc.) trotter) through AquaCrop in northern ethiopia. *Experimental Agriculture* **48**, 222-237.

Tubiello, F. N., and Ewert, F. (2002). Simulating the effects of elevated CO2 on crops: approaches and applications for climate change. *European Journal of Agronomy* **18**, 57-74.

Twomlow, S., Steyn, J., and Du Preez, C. (2006). Dryland Farming in Southern Africa. Second Edition. *In* "Dryland Agriculture" (G. A. Petersen, W. P. Unger and W. A. Payne, eds.), pp. 769-836. Agronomy Monogram No. 23, American Society of Agronomy, Madison, Wisconsin.

Usman, M. T., and Reason, C. J. C. (2004). Dry spell frequencies and their variability over southern Africa. *Climate Research* **26**, 199-211.

Van Gaelen, H., Tsegay, A., Delbecque, N., Shrestha, N., Garcia, M., Fajardo, H., Miranda, R., Vanuytrecht, E., Abrha, B., and Diels, J. (2014). A semi-quantitative approach for modelling crop response to soil fertility: evaluation of the AquaCrop procedure. *The Journal of Agricultural Science*, 1-16.

Vanuytrecht, E. (2013). Crop Responses to Climate Change: Impact on agricultural production and the soil water balance in the Flemish Region of Belgium, Leuven University, Leuven.

Vanuytrecht, E., Raes, D., Steduto, P., Hsiao, T. C., Fereres, E., Heng, L. K., Garcia Vila, M., and Mejias Moreno, P. (2014a). AquaCrop: FAO's crop water productivity and yield response model. *Environmental Modelling & Software* **62**, 351-360.

Vanuytrecht, E., Raes, D., Willems, P., and Geerts, S. (2012). Quantifying field-scale effects of elevated carbon dioxide concentration on crops. *Climate Research* **54**, 35-47.

Vanuytrecht, E., Raes, D., Willems, P., and Semenov, M. A. (2014b). Comparing climate change impacts on cereals based on CMIP3 and EU-ENSEMBLES climate scenarios. *Agricultural and Forest Meteorology* **195–196**, 12-23.

Varis, O., Kajander, T., and Lemmelä, R. (2004). Climate and Water: From Climate Models to Water Resources Management and Vice Versa. *Climatic Change* **66**, 321-344.

Veldman, R. (2012). Dynamics in wetland agriculture: competition and desiccation: A case study of household dynamics, agricultural intensification and competition for resources in wetland agriculture in Badwa dambo, Malawi, Wageningen, Wageningen University, The Netherlands.

Vincent, K., Cull, T., Chanika, D., Hamazakaza, P., Joubert, A., Macome, E., and Mutonhodza-Davies, C. (2013). Farmers' responses to climate variability and change in southern Africa - is it coping or adaptation? *Climate and Development* **5**, 194-205.

Von Storch, H. (1995). "Misuses of statistical analysis in climate research," Springer, Berlin.

Vrieling, A., de Leeuw, J., and Said, M. Y. (2013). Length of Growing Period over Africa: Variability and Trends from 30 Years of NDVI Time Series. *Remote Sensing* **5**, 982-1000.

VSNInternational (2013). GenStat for Windows 16th Edition. VSN International, Hemel Hempstead, UK. Web page: GenStat.co.uk.

Wang, B., Wan, H., Ji, Z., Zhang, X., Yu, R., Yu, Y., and Liu, H. (2004). Design of a new dynamical core for global atmospheric models based on some efficient numerical methods. *Science in China, Series A (Mathematics, Physics, Astronomy)* **47**, 4-21.

Wenzel, W. (2003). Rainfall and the prediction of sorghum yield in South Africa. *South African Journal of Plant and Soil* **20**, 38-40.

Wilks, D. S., and Wilby, R. L. (1999). The weather generation game: a review of stochastic weather models. *Progress in Physical Geography* **23**, 329-357.

Willems, P., Arnbjerg-Nielsen, K., Olsson, J., and Nguyen, V. T. V. (2012). Climate change impact assessment on urban rainfall extremes and urban drainage: Methods and shortcomings. *Atmospheric Research* **103**, 106-118.

Williams, J. R., Jones, C. A., Kiniry, J. R., and Spanel, D. A. (1989). THE EPIC CROP GROWTH-MODEL. *Transactions of the Asae* **32**, 497-511.

Wiyo, K. A. (1999). Effect of tied-ridging on soil water status and maize yield under Malawi conditions, KULeuven, Leuven.

Wiyo, K. A., Kasomekera, Z. M., and Feyen, J. (1999). Variability in ridge and furrow size and shape and maize population density on small subsistence farms in Malawi. *Soil & Tillage Research* **51**, 113-119.

Wiyo, K. A., Kasomekera, Z. M., and Feyen, J. (2000). Effect of tied-ridging on soil water status of a maize crop under Malawi conditions. *Agricultural Water Management* **45**, 101-125.

WMO (1988). Analyzing long time series of hydrological data with respect to climate variability. WCAP-3, WMO/TD No. 224, World Meteorological Organisation, Geneva, p 12.

Woltering, L. (2005). Estimating the influence of on-farm conservation practices on the water balance: Case of the Mzinyathini catchment in Zimbabwe. M.Sc, Delft University of Technology, The Netherlands.

Wondumagegnehu, F., Tsegay, A., Ashebir, D., Tekie, H., Gebre, A., Kiros, M., Geerts, S., Raes, D., Nyssen, J., and Deckers, J. (2007). Household water harvesting structures in Geba catchment. Tigray Livelihood Papers No. 5, VLIR – Mekelle University IUC Programme, 28 p.

Wortmann, C., Mamo, M., Mburu, C., Letayo, E., Abebe, G., Kayuki, K. C., Chisi, M., Mativavarira, M., Xerinda, S., and Ndacyayisenga, T. (2009). Atlas of Sorghum Production in Eastern and Southern Africa. *The Board of Regents of the University of Nebraska, University of Nebraska-Lincoln*.

Xiong, W., Holman, I., Conway, D., Lin, E., and Li, Y. (2008). A crop model cross calibration for use in regional climate impacts studies. *Ecological Modelling* **213**, 365-380.

Zinyengere, N., Crespo, O., Hachigonta, S., and Tadross, M. (2014). Local impacts of climate change and agronomic practices on dry land crops in Southern Africa. *Agriculture Ecosystems & Environment* **197**, 1-10.

Annex I: Farmer survey questionnaire

SMALL HOLDER FARMER ADAPTATION TO CLIMATE CHANGE AND IMPLICATION FOR CEREAL PRODUCTION

Name of enumerator ____________________________Date_________________________________

INTRODUCTION

Good (morning, afternoon). My name is __________. I am a student from Belgium conducting a research on smallholder farmer's adaptation to climate change and its implication on cereal production. I would like to chat with you on this topic. The information gathered will be used to identify trends on how the smallholder farmers are adapting to climate change in their farming practice. This will be useful to have general adaptation patterns in the smallholder sector of farming and challenges and opportunities in order to suggest ways of improving cereal production in Malawi and other countries as well. While the general conclusions of the study may be used to help formulate government policy recommendations, all the specific information you provide will be treated confidentially. We hope that you will be willing to help us with this research.

MAWU OYAMBA

Ine ndine__________________, ndachokera kusukulu ya ku Belgium. Ndabwera kudzaphunzira za ulimi kuchokera kwa inuyo.Ndimafuna kupempha nawo kuti ticheze nanu pa nkhani zokhudza ulimi ndi kusintha kwa nyengo. Ndikufuna ndidziwe mmene mwasinthila mmalimidwe anu, mavuto amene mukukumana nawo ndi mmene mukuwonera kuti ulimi ungapite patsogolo. Zimenezi zithandiza boma kukhala ndi chithunzi chabwino cha m'mene zinthu zilili m'dela lanu lino. Komanso, zithandiza boma ndi mayiko osiyansiyana popanga ndondomeko zopititsa patsogolo ntchito za ulimi kwenikweni wa alimi ang'onoang'ono. Tikufusaninso zinthu zina zokhudza umoyo wanu wapakhomo pano. Chonde masukani kutiuza zonse zimene mukudziwa, zidzasungidwa mwachinsinsi.

Village_____________________________
T/A__________________________________

A. DEMOGRAPHIC INFORMATION

1 **Name of household head**________________________________

2 **Type of household** [1] Male-headed [2] Female-headed [3] Child-headed

3 **Name of respondent if respondent is not household head** ____________________

4 **Gender of respondent** [1] Male [2] Female

5 **Relationship of respondent to household head** [1] Spouse [2] Son/daughter [3] Son/daughter in law [4] Grandchild [99] Other: specify_________________________

6 **Age of the respondent**_______________________________

7 **Marital status of the respondent** [1] Single [2] Married [3] Divorced [4] Widowed [5] Separated

8 **Education level of the respondent** [1] None [2] Junior primary [3] Senior primary [4] Secondary [5] Tertiary [6] Adult literacy [99] Other: Specify _________________

9 **Number of people in the household _________**

I would like to ask you about the household members who normally live and eat together in this dwelling during the last year, including those who temporarily migrate and students who board away.								
Name	**Age/DOB**	**Sex** [1] M [2] F	**Relation to head**	**Highest level of education**	**Residence status**	**Years of residence**	**Main Occupation**	**Marital status**

Key

Relationship to head	***Education***	***Residential status***	***Occupation***	***Marital status***
[1] Head	*[1] None*	*[1] Resident*	*[1] Peasant farmer*	*[1] Single*
[2] Spouse	*[2] Junior primary1-4*	*[2] Resident at school*	*[2] Semi-commercial farmer (e.g., cash crop grower)*	*[2] Married*
[3] Father	*[3] Senior 5-8 primary*	*[3] Immigrant/settler*	*[3] Wage labourer/worker*	*[3] Divorced*
[4] Mother	*[4] Secondary*	*[4] Visiter*	*[4] Fisherman*	*[4] Widowed*
[5] Son/daughter	*[5] Tertiary*	*[5] Resident worker*	*[5] Artisan/carpentry*	*[5] Separated*
[6] Son/daughter in-law	*[6] Adult Literacy*	*[6] Hired labourer*	*[6] Housewife*	
[7] Uncle	*[99] Other: specify*	*[99] Other: specify*	*[7] Small scale business*	
[8] Worker /labourer			*[8] Large scale business*	
[9] Grandchild			*[9] Student*	
[10] Relative			*[10] None*	
[11] Visitor			*[99] Other: specify*	
[12] Brother/sister				
[99] Other: specify				

10 **What are the sources of income in this household?** *(Mark all sources)*

[1] Business [2] Employment [3] Casual labour [4] Remittance [5] Farming [6] Consultancies [7] House rentals and [8] Minibus operations [99] Others: specify

11 What is your household average total income per month from various sources above?

Source	**Monthly income**	**Annual Income**	**Annual income** *[1] < MK5,000 [2]MK5,000 to MK 10,000 [3] MK10,000 to MK50,000 [4] MK51,000 to MK100,000 [5] MK 101,000 to MK250,000 [6] MK 251,000 to MK500,000 [7] > MK500,000 [8] Do not know*
[1] Business			
[2] Employment			
[3] Casual labour			
[4] Remittance			
[5] Farming			
[6] Consultancies			
[7] House rentals			
[8] Mini-bus			
[9] Transportation			
[99] Others: specify			
Total			

12 Which assets do you possess? (*Muli ndi katundu wanji?)*

Assets	**Numbers**	**Assets**	**Numbers**
[1] Vehicle		[8] Sofa set/chairs	
[2] Own house		[9] Beds	
[3] Television set		[10] Washing machine	
[4] Radio		[11] Ox-cart	
[5] Cassette player		[12] Woodlot	
[6] Bicycle		[13] Sewing machine	
[7] Cell phone		[99] Others: specify	

B. CROPPING PRACTICES

13 How long have you been involved in farming? (*Mwakhala mukulima kwa zaka zingati?)*

[1] 1 year [2] 1 to 3 years [3] 3 to 5 years [4] 6 to 10 years [5] As long as I can remember

14 What type of labour do you employ? (*Mukamalima mumagwiritsa ntchito chain?)*

[1] Family labour [2] Temporary hired labour [3] Permanent Hired labour [4] Animal power [5] Mechanical Power

15 How many fields do you have, distance from the house, sizes and how did you acquire the field? *(Use the key below) (Muli ndi minda ingati, mitunda yake yayitali bwanji kuchokera ku nyumba, yayikulu bwanji, munaipeza bwanji?)*

Field number ***(Munda)***	**Distance from the house** ***(Mtunda kuchokera ku nyumba)***	**Size** ***(Kukula)***	**Acquisition (*Mapezedwe)***	**How is the field located** ***(Uli potani)***

Key

Size (Kukula)	***Acquisition type (Mmapezedwe)***	***Where the plot is situated (Uli potani)***
[1] Less than half hectare *[2] Half-1 hectare* *[3] 1-3 hectares* *[4] 3-5 hectares* *[5] Greater than 5 acres*	*[1] Given by village headman/chief* *[2] Given/inherited from maternal relative* *[3] Given/inherited from paternal relative* *[4] Borrowed* *[5] Rented* *[99] Other: specify*	*[1] On flat land* *[2] On a gentle slope* *[3] Near a stream* *[4] On a hill/steep slope* *[99] Other: specify*

16 What types of crops do you grow? (*Mumalima mbeu za mtundu wanji?)*

[1] Maize [2] Sorghum [3] Cassava [4] Tobacco [5] Sweet potato [6] Soya [7] Ground nuts [8] Pigeon peas [9] Beans [10] Millet [11] Vegetables [99] Others: specify

17 **What type of crops did you grow in the past three years on each plot and plan to grow next year?** ***(Mumalima mbeu zanji zaka zitatu zapitazo pa munda uliwonse ndipo mapulani a chaka chino)***

Plot number	**Planned for 2011-2012**	**2010-2011**	**2009-2010**	**2008-2009**	**2007-2008**

18 **What type of fertiliser do you apply?** ***(Mumathira manyowa kapena feteza?)***
[1] Organic [2] Inorganic [3] None *(go to question 20)*

19 **To what crops and how long have you been applying the above mentioned fertiliser and why?** ***(Mwakhala mukuthira fetelazayu/manyowa kwa nthawi yayitali bwanjiµ?)***

Crop	Type of fertiliser	Length	Reason
[1] Maize			
[2] Sorghum			
[3] Cassava			
[4] Tobacco			
[5] Sweet potato			
[6] Soya			
[7]Groundnuts			
[8] Pigeonpeas			
[9] Beans			
[10] Millet			
[11]Vegetables			
[99] Others: specify			

20 **What type of maize variety did you grow last season? (*Munadzala mtundu wanji wa chimanga?)***
[1] Local [2] Hybrid [3] Composite

21 **If hybrid variety was grown, specify the variety ___________________________**

22 **What was the size of the maize field? *(Mumunda waukulu bwanji?)***
[1] < 0.5 hectare [2] 0.5-1 hectare [3] 1-3 hectares [4] 3-5 hectares [5] > 5 hectares

23 **What type of sorghum variety did you grow last season? *(Mumalima mtundu wanji wa mapira?)***
[1] Local [2] Hybrid [3] Composite

24 **If hybrid variety was grown, specify the variety __________________________________**

25 **What was the size of the sorghum field? *(Kodi munda wa mapira ndi waukulu bwanji?)***
[1] < 0.5 hectare [2] 0.5-1 hectare [3] 1-3 hectares [4] 3-5 hectares [5] > 5 acres

26 **How many kg of each maize/sorghum variety grown in the past three years did you harvest? *(Munakolola chimanga/mapira chambiri bwanji zaka zitatu zapitazi?)***

Crop	**2010-2011**	**2009-2010**	**2008-2009**	**2007-2008**
Maize				
Sorghum				

27 **How did you compare this years harvest to the past 10 years? *(Mungathe kufananitsa bwanji mmene mukukolera masuku ano ndi zaka khumi zapitazo?)***
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28 **For the last season, under what farming system was maize/sorghum planted?** ***(Kodi munadzala bwanji chimanga/mapira chaka chathachi?)***

Maize	**Sorghum**	**Other cereals**
[1] Pure stand [2] Intercropped with ground nuts [3] Intercropped with pulses [4] Intercropped with sweet potato [5] Intercropped with soya [6] Intercropped with cassava [7] Planted under agroforestry	[1] Pure stand [2] Intercropped with ground nuts [3] Intercropped with pulses [4] Intercropped with sweet potato [5] Intercropped with soya [6] Intercropped with cassava [7] Planted under agroforestry	[1] Pure stand [2] Intercropped with ground nuts [3] Intercropped with pulses [4] Intercropped with sweet potato [5] Intercropped with soya [6] Intercropped with cassava [7] Planted under agroforestry

29 **How long have you been practicing the above mentioned practice?** ***(Mwakhala mukudzala chonchi nthawi yayitali bwanji?)*** ____________________years

30 **What factors influenced your cropping pattern?** ***(Ndichani chimene chinakupangitsani kuti muzilima chonchi?)***

[1] Availability of labour [2] Past rainfall patterns [3] Anticipated prices for the crops

[4] Household food security [5] Household income needs [6] Availability of inputs [7] Advice of extension personnel [8] None [9] Using every space; maximizing space [99] Others: specify________________________

31 **In which month do you normally start preparing your fields?** ***(Mumasosa liti munda wanu kuti mudzalemo mbewu?)*****__________________________________**

32 **What factors do you consider to plant your maize/sorghum crop?** ***(Mumayang'ana chani kuti mukadzale kumunda kwanu?)***

Maize	Sorghum	Other cereals (specify)______
[1] With the first rains [2] When I feel there is enough moisture [3] December regardless of the rains [4] November regardless of the rains [99] Others: specify__________ ___________________________	[1] With the first rains [2] When I feel there is enough moisture [3] December regardless of the rains [4] November regardless of the rains [99] Others: specify__________ ___________________________	[1] With the first rains [2] When I feel there is enough moisture [3] December regardless of the rains [4] November regardless of the rains [99] Others: specify__________ ___________________________

33 **Do you harvest enough maize/sorghum to eat for the whole year** ***(Kodi mumakakolola zokwanira chaka chonse?)***

[1] Always *(go to question 36)* [2] Sometimes [3] Never

34 **If no, in which month do you run out of maize/sorghum?** ***(Ngati ayi, ndi mwezi uti zimapezeka kuti zatha?)*****___________________________**

35 **During these periods of food shortage, how do you cope with maize/sorghum shortage?** ***(Nthawi ya chakudya chochepayi, mumapanga bwanji kuti mupilire mpaka kufikira nthawi ya chakudya chambiri?)***

[1] Cash purchase [2] Supplement with dimba maize [3] Donation from relative [4] Wait for govt relief maize [5] Food for labour (ganyu) [6] Use of hunger crops [7] Reduce frequency and type of meals [8] Migrate to towns for employment [9] Sell household assets [10] Sell livestock [11] Firewood sells [99] Others: specify___________________________________

36 In case of surplus, what do you do with such surplus? ***(Ngati mwakolola zochuluka, mmatani nazo?)***

[1] Sale maize [2] Donate to relatives and friends [3] Exchange labour for food [4] Keep for the next season [99] Others: specify_________________________________

37 Can you estimate how much your household spent on the following items last season? ***(Kodi mwawononga ndalama zingati po zinthu izi zaka zapitazo?)***

Item	**2010-2011 Cost in Kwacha**	**2009-2010 Cost in Kwacha**
[1] Seed		
[2] Fertiliser		
[3] Transport		
[4] Manure		
[5] Labour		
[6] Inputs		
[7] Pesticides		
[99] Others		

38 Are there any changes that you have noticed weather patterns for the past 10 years? ***(Kodi mwawonapo kusintha kulikonse mmene nyango ilili masiku ano, mukafanizira ndi zaka 10 zapitazo?)***

[1] Yes [2] No *(go to question 43)*

39 If yes, what type of changes have you noticed? ***(Ngati eya, chasintha ndi chain?)***

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40 Are the changes contributing positively to your harvest? ***(Kodi kusinthaku kwakhala kwa ubwino /ku zokolola zanu mu ulimi wanu?)***

[1] Yes*(go to question 43)* [2] No

41 **If no, what have you done to adapt to the changes?** ***(Ngati kusinthaku kwakubwezerani mmbuyo, mwapangapo chain kuti muthe kupitiliza kukolora mmene munkapangira zaka khumi zapitazo?)***
[1] Nothing has been done [2] Planting multiple crops (spreading the risk) [3] Planting early maturing maize variety [4] Applying more fertiliser [5] Staggered planting/different dates [6] Early crop planting [7] Changed ridge spacing [8] Change spacing and number of plants (one-one planting) [9] Timely weeding [10] Making box ridges [11] Applying manure [12] Practicing conservation agriculture [99] Others: specify____________________________

42 **What can be done to address the changes?** ***(Mukuwona ngati chofunika kuchita ndi chain kuti tithe kupititsa patsogolo ulimi ngakhale nyengo ikusitha?)***
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43 **What are the main problems that you face in your rainfed farming?** ***(Kodi ndi mavuto ati amene mukukumana nawo mu ilimi wanu?)***
[1] Pest and diseases [2] Lack of inputs (eg seed, fertiliser etc) [3] Money shortage [4] Labour shortage [5] Transport shortage [6] Poor rainfall/water shortage [7] Erosion/gullies/flooding [8] Soil fertility decline [9] Marketing problems [10] Lack of extension services [11] Land shortage [12] Post harvest storage [99] Others: specify_______________________________

C. SOIL AND WATER

44 **Do you practice soil and water conservation in your field?** ***(Kodi mmateteza nthaka mu ulimi wanu?)***
[1] Yes [2] No *(go to question 47)*

45 **What soil and water conservation techniques are you practicing in your field?** ***(Ndi njira ziti zimene mumatsata?)***
[1] Mulching [2] Contour bunding [3] Contour ridging [4] Box ridges [5] Pit planting [6] Hedgerows/boundary trees/vertiver grass [7] Alley cropping [8] Silt traps in gullies [9] Minimum tillage [10] Agroforestry [11] Crop rotation [99] Others: specify ____________
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46 **What are the reasons for introducing these techniques in you field?** ***(Nchifukwa chani munayamba kupanga zimenezi?)***
[1] To conserve the soil/rehabilitate land [2] To conserve water in the field [3] To improve soil fertility [4] Source of fuel wood and poles [5] Fodder for livestock [6] Source of food (fruits) [7] We always do it that way [8] Forced by extension workers [99] Others: specify
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47 **Are there any factors that prevent you from adapting to other techniques?** ***(Kodi pali china chilichonse chimene chikukukanikitsani kupanga njira zina zotetezera nthaka?)***

[1] Yes [2] No *(go to question 49)*

48 If yes, what are the factors? ***(Ngati eya, ndi chain chikukulepheretsa?)***

[1] Shortage of labour [2] Lack of information [3] Lack of money [4] Lack of proper equipment [5] Small land holding [6] Insecure land rights [99] Others: specify____________

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49 Have you changed your land husbandry practices to ensure a harvest during years of low and erratic rainfall? ***(Kodi munasinthako mamalimidwe kuti mukolore china chake nthawi yovuta mvula?)***

[1] Yes [2] No *(go to question 52)*

50 If yes, in what ways have you tried to retain rainwater in your field? ***(Ngati eya, mwapangapo chiyani kuti muwonetsetse kuti madzi a mvula sanapite onse nthawi yamvula)***

[1] Crop residues in the field [2] Timely scarification (kupalira) [3] Timely banking (kuundira) [4] Re-aligned ridges with marker ridges [5] Bigger ridges [6] Box ridges [7] Avoid weeding [99] Others: specify____

51 How efficient are methods that you are practicing? ***(Kodi njira zimene mukupangazi zikukuthandizani bwanji?)***

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52 Over the years, can you say you have seen changes in the way people around these village have changed their farming practices. If yes what are they and the reasons for changing? ***(Pa zakazi mwaonapo anthu akusintha malimidwe awo? Ngati eya, asintha chani ndipo chifukwa chake chani?)***

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D LIVESTOCK

53 Do you have livestock? ***(Muli ndi ziweto?)***

[1] Yes [2] No *(go to question 60)*

54 What type of livestock? ***(Muli ndi ziweto zanji?)***

[1] Cattle [2] Goats [3] Chicken [4] Rabbits [5] Pigeons [6] Ducks [7] Sheep [8] Guinea Fowl [9] Pigs [10] Turkey [99] Others: specify____

55 **How do you feed the animals?** ***(Mumadyetsa bwanji ziweto zanuzi?)***
[1] Free range [2] Stall feeding [3] Tied to a rope to graze [4] Graze them in the wetlands [99] Others: specify____

56 **How do you water your animals?** ***(Kodi ziwetozi zimamwera kuti?)***
[1] Fetch water from the source [2] Take the animals to water source

57 **Is the water readily available for the animals?** ***(Kodi madzi omwetsa ziwetozi, amapezeka nthawi zones?)***
[1] Yes *(go to question 60)* [2] No

58 **If no, what do you think are the problems?** ***(Ngati ayi, mukuona ngati vuto lili pati?)***
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59 **How can these problems be solved?** ***(Mukuganiza kuti mavuto amenewa angapewedwe/kuthetsedwa bwanji?)***
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60 **Do you think changes in weather have affected the way people keep animals?** ***(Kodi mukuganiza kuti kusintha kwa nyengo kwa pangitsa mawetedwe a ziweto kwa ntundu wina?)***
[1] Yes [2] No *(go to question 62)*

61 **If yes, what are the changes?** ***(Chasintha ndi chain?)***
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E Water and sanitation

62 What is the major source of household water supply in the wet and dry season? ***(Kumene mumadalira kupeza madzi ogwiritsa ntchito pakhomo pano nthawi ya dzinja ndi chilimwe kuti)***

Water source	**Tick source**		**Distance to source**	**Time to draw water (hours or minutes)**	**Amount of containers collected per day**	**Type of container**
	Wet season	Dry season				
[1] Community stand pipe						
[2] Unprotected well						
[3] Protected well						
[4] Borehole						
[5] Spring;						
[6] River/stream						
[7] Pond/lake;						
[8] Dam						
[9] Rain water harvest						
[99] Others: specify						

63 What do you use the water for? ***(Mumagwiritsa ntchito yanji?)***

Water use	**Main water source**
[1] Domestic use	
[2] Watering vegetable garden	
[3] Moulding bricks	
[4] Construction work	
[99] Others: specify	

64 Do you experience water shortage? ***(Pali nyengo zina zomwe madzi amasowa?)***

[1] Yes [2] No *(go to question 68)*

65 If yes, which months of the year do you normally experience water shortages? ***(Madzi amasowa mumiyezi yanji?)***

Jan – Feb – Mar – Apr – May – June – July – Aug – Sept – Oct – Nov – Dec

66 **What alternative sources of water do you use in times of water shortage?** ***(Mumatunga kuti madzi akasowa?)***

Water source	**Tick source**
[1] Piped water	
[2] Unprotected well	
[3] Protected well	
[4] Borehole	
[5] Spring;	
[6] River/stream	
[7] Pond/lake;	
[8] Dam	
[9] Rain water harvest	
[99] Others: specify	

67 **What has been your response to water shortages?** ***(Mumatani madzi akamasowa?)***
[1] Washing less frequently [2] Reducing amount of water per use [3] bathing less frequently [4] water recycling [99] Others: specify___________________________

F Agroforestry

68 **Do you have planted trees?** ***(Muli ndi mitengo chichita kudzala?)***
[1] Yes [2] No *(go to question 73)*

69 **Where are the trees planted?** ***(Mitengoyo inadzalidwa kuti?)***
[1] Around the house [2] Scattered in the field [3] In the dimba
[99] Others: specify___________________________

70 **Who planted the trees?** ***(Anadzala mitengoyi ndani?)***
[1] Yourself [2] Your Spouse [3] Your father [4] Your mother [5] Grandparents [6] Relatives [99] Others: specify___________________________

71 **What type of trees do you have?** ***(Muli ndi mitengo yanji?)***
[1] Gmelina [2] Eucalyptus (bluegum) [3] Pine [4] Acacias (msangu) [5] Sesbania [6] Fruit trees [99] Others: specify___________________________

72 **Why were the trees planted?** ***(Chifukwa chani mitengoyi inadzalidwa?)***
[1] Source of firewood [2] Source of poles [3] Source of medicine [4] Source of fruits [5] To conserve the soil [6] To conserve water [7] To improve soil fertility [8] To provide shade [9] Fodder for animals [99] Others: specify___________________________

73 **Where do you get information about farming practices?** ***(Uthenga wa za ulimi mumaumvera kuti?)***

[1] Radio/Television [2] Newspaper [3] Extension workers from the government [4] Friends [5] Non Governmental Organisations [6] School [7] University researchers [8] inheritance [9] None [99] Others: specify____

74 **Do you have any questions/comments?** ____
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Thank you very much for your time and we have learnt a lot from you. Bye!

Zikomo kwambiri chifukwa chotilora kucheza nanu, ife taphunzira zambiri kuchokera kwa inu. Tsiku labwino!

Annex II: Experimental plot layouts

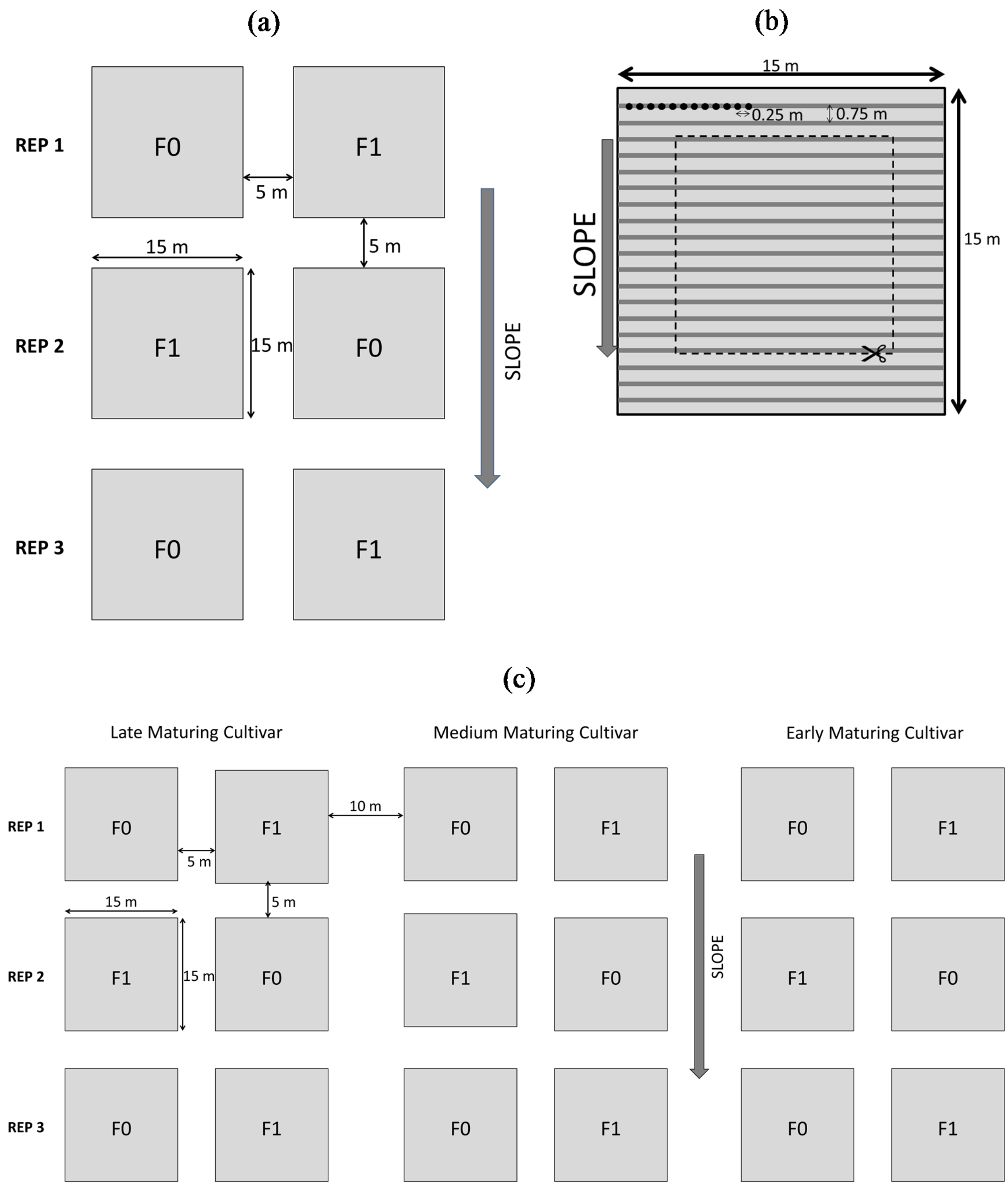

Figure 10-1: Experimental plot layouts used: (a) 2010/11 and 2011/12 and (c) 2012/13 growing seasons. The letter F, denotes fertilizer and R replication. F1 represents full dose and F0 half dose recommended fertilizer application rate. REP1, REP2 and REP3 represents replication. (b) Is a zoomed plan of a typical plot which shows ridge and plant spacing; darker boarder lines represents the guard rows and harvested area is shown in dotted lines.

Annex III: Statistical analysis of future climate data for LARS-WG approach for central Malawi

Table 10-1: Mean monthly rainfall statistical analysis for LARS-WG approach for central Malawi

Month	Mean Observed	Standard deviation	Mean Generated	Standard deviation	t-Statistic	P-Value
January	235.28	81.152	232.21	86.912	0.199	0.842
February	191.44	75.725	204.69	78.303	-0.945	0.346
March	149.59	88.218	156.94	80.623	-0.489	0.625
April	40.99	32.405	46.21	34.656	-0.848	0.398
May	11.25	29.889	16.12	37.135	-0.76	0.449
June	0.73	1.659	0.36	0.997	1.656	0.1
July	0.81	2.222	0.7	2.536	0.24	0.811
August	0.14	0.404	0.22	0.612	-0.796	0.428
September	1.29	3.962	1.84	5.014	-0.628	0.531
October	10.73	13.78	10.63	13.137	0.041	0.967
November	70.33	50.726	64.07	59.476	0.602	0.548
December	176.39	83.599	150.01	86.079	1.695	0.092

Table 10-2: Mean monthly minimum air temperature statistical analysis for LARS-WG approach for central Malawi

Month	Mean Observed	Standard deviation	Mean Generated	Standard deviation	t-Statistic	P-Value
January	17.89	0.653	17.86	0.157	0.303	0.762
February	17.46	0.691	17.52	0.144	-0.832	0.407
March	17.15	1.044	16.84	0.227	2.814	0.006
April	14.3	1.296	14.27	0.339	0.267	0.79
May	11.59	1.068	11.25	0.258	3.025	0.003
June	8.93	1.115	8.99	0.231	-0.524	0.601
July	8.98	0.965	9.2	0.234	-2.186	0.03
August	10.27	0.995	10.64	0.238	-3.583	0
September	13.47	1.08	13.37	0.242	0.924	0.357
October	15.82	1.113	16.02	0.247	-1.709	0.09
November	17.98	1.078	17.82	0.199	1.453	0.149
December	18.23	0.885	18.22	0.181	0.076	0.94

Table 10-3: Mean monthly maximum air temperature statistical analysis for LARS-WG approach for central Malawi

Month	Mean Observed	Standard deviation	Mean Generated	Standard deviation	t-Statistic	P-Value
January	26.76	0.911	26.76	0.203	0.021	0.983
February	26.98	0.817	26.95	0.232	0.35	0.727
March	26.96	0.817	26.88	0.183	0.955	0.341
April	26.39	0.712	26.38	0.186	0.092	0.927
May	25.86	1.007	25.5	0.207	3.406	0.001
June	23.76	0.748	23.74	0.193	0.275	0.784
July	23.79	0.639	24.06	0.172	-3.865	0
August	25.85	0.717	26.19	0.177	-4.508	0
September	29.01	0.785	28.83	0.195	2.188	0.03
October	30.31	0.822	30.32	0.188	-0.15	0.881
November	29.9	1.235	29.87	0.292	0.222	0.825
December	27.63	1.114	27.7	0.269	-0.584	0.56

Annex IV: Publication list

Papers published in international, reviewed academic journals

Fiwa, L., Vanuytrecht, E., Wiyo, K.A., Raes, D. (2014). Effect of rainfall variability on the length of the crop growing period over the past three decades in Central Malawi. *Clim Res* (62): 45 – 58.

Papers submitted to international, reviewed academic journals

Wiyo, K.A**, Fiwa, L** and Mwase S (2015). Solving Deforestation, Protecting and Managing Key Water Catchments in Malawi Using Smart Public and Private Partnerships. Submitted to *Journal of Sustainable Development*

Meeting abstracts, presented as poster/papers at international scientific conferences and symposia, published in proceedings

Fiwa, L and Kamoyo, K.J (2011). Contribution of conservation agriculture in rainfed crop water productivity improvement. A case study of maize rainfed system in central Malawi, Conference Proc. Increasing Agricultural Productivity and enhancing food security in Africa by IFPRI – November 2011, Addis Ababa, Ethiopia

Corzo Perez G, **Fiwa L**, Wiyo K, Raes D, Vanuytrecht E, Geerts S, Van Lanen H (2011). Comparison of spatio-temporal patterns of droughts in Malawi and el Niño Oscillation index. Conference Proc. EGU General Assembly, June 2011, Vienna. *Geophysical Research Abstracts* 13: EGU2011-13783

Fiwa L, Raes D, Wiyo K.A., Vanuytrecht E, Willems P, and Geerts S (2010). Performance evaluation of General Circulation Models in Malawi for an agro-based impact analysis. Conference Proc. Building Capacity for Climate Change interventions November, 2010, Lilongwe, Malawi